The relevance of a proper use of concepts and terms



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The relevance of a proper use of concepts and terms

1. The scientific language

2. Concepts and terms that are often confused

3. Evapotranspiration

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The scientific language

It must be clear, rigorous and precise.

1. Clarity A scientific paper must be published and understood.

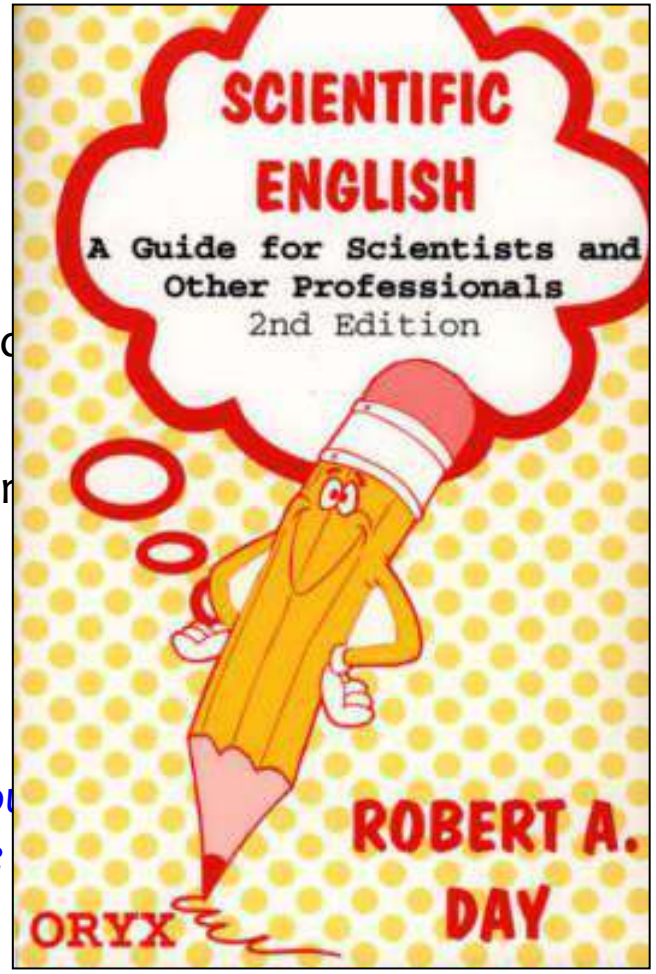
Key rule: avoid waste words; use simple, short words and

- Words

methodology	*method*
equivalent	*equal*
finalize	*end*
perform	*do*
utilize	*use*

- Expr

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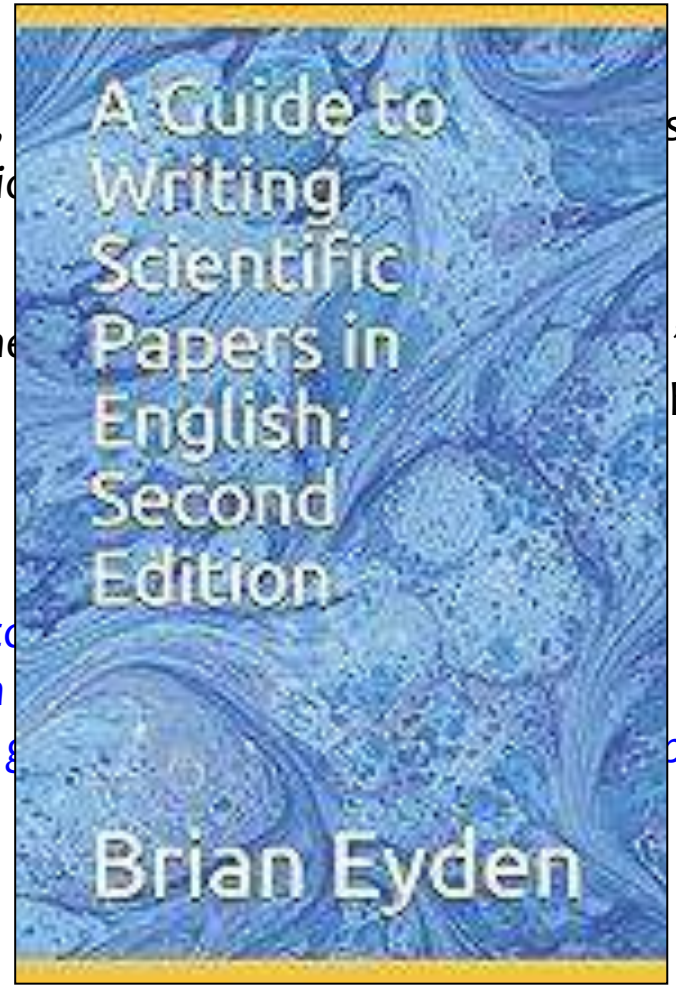
The scientific language

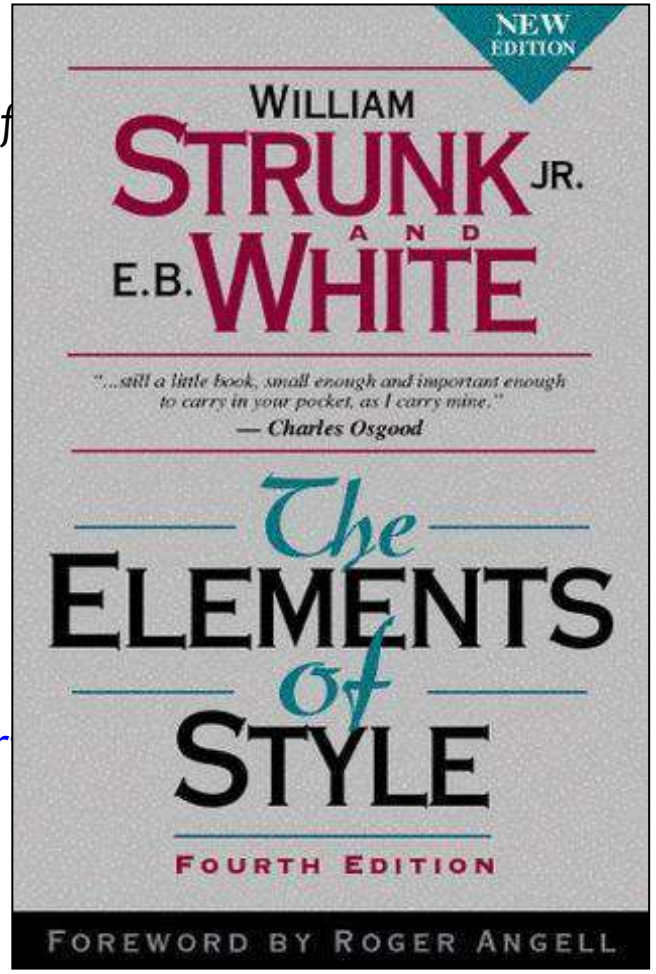
Keep it simple:

"State your facts as simple as possible, s of
or literary ornaments in a research artic

R.B. McKerrow
"The best English is that which gives the "
he

because better than *acc*
for example " *an*
useful " *of g* por





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The scientific language

2. Rigor

- Use symbols and units accepted by both the scientific community and the journal to which the manuscript is going to be submitted.

- Do not use different names for the same thing.

the irrigation period - *the irrigation season*
the software - *the programme*
the tree - *the plant*

- Use British English or American English, according to the journal to which the manuscript is going to be submitted, but do not mix them.

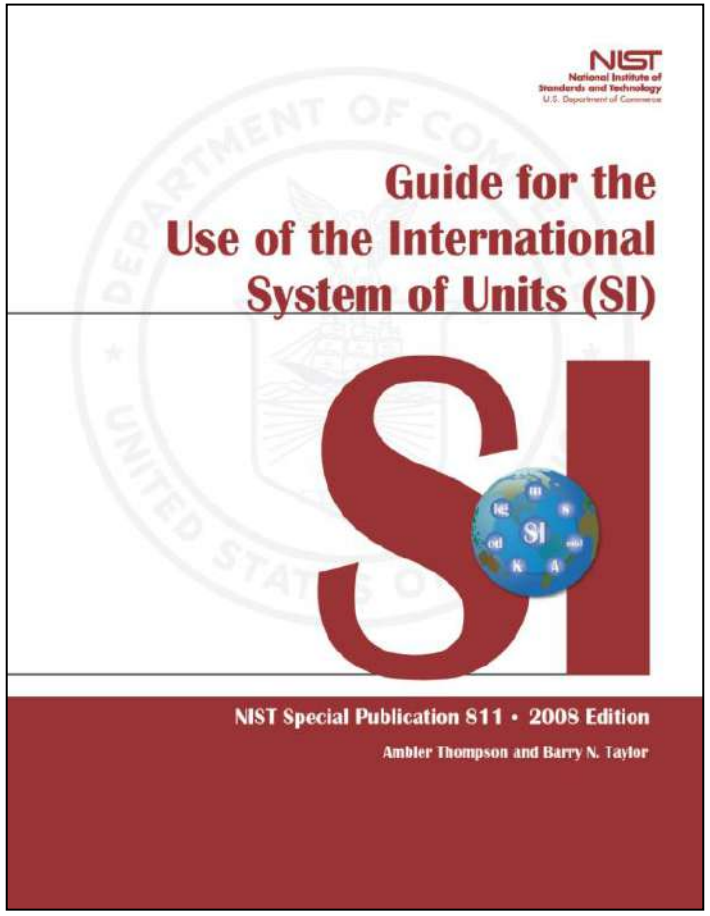
program vs. *programme*
color vs. *colour*
minimize vs. *minimise* (Both accepted in the UK)

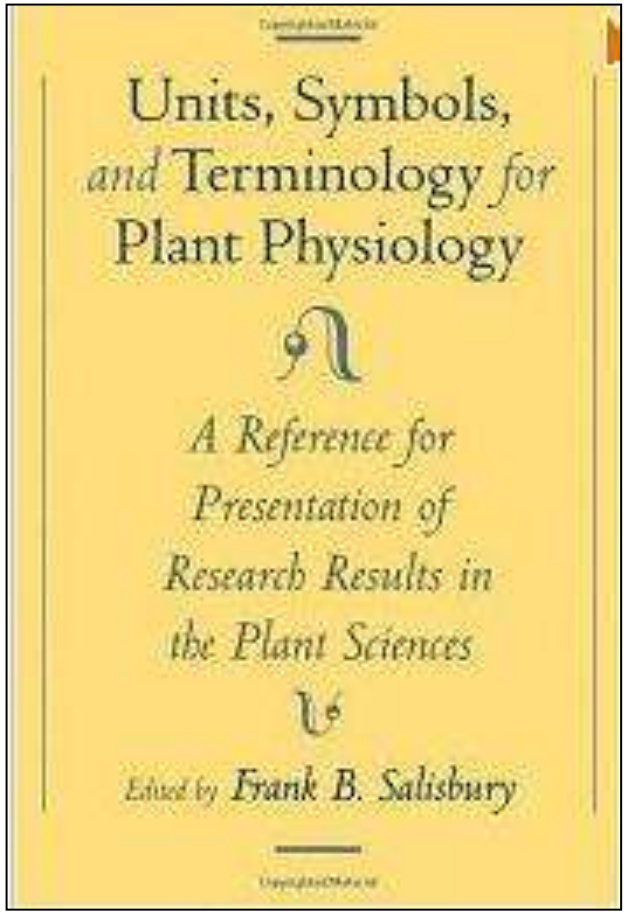
- Use terms, concepts and definitions properly. This says a lot on the quality of your work.

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The scientific language

Consult reliable literature to be sure on the correct symbols and units.





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The scientific language

This includes review articles and key articles on the topic, written by top experts.



Agricultural and Forest Meteorology 150 (2010) 135–151

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Review

Irrigation scheduling from stem diameter variations: A review

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ARTICLE INFO

Article history:
Received 12 June 2009
Received in revised form 26 October 2009
Accepted 9 November 2009

Keywords:
Maximum daily shrinkage
Trunk growth rate
Dendrometer
LVDT sensor
Water-stress indicator
Sap flow
Transpiration

ABSTRACT

Precise irrigation is essential in arid and semi-arid areas where water is scarce. This has impelled the scientific community to develop new technologies for scheduling irrigation. Of these, the ones relying on plant-based water-stress indicators have been found to have the greatest potential. Thus, measurements of stem water content, canopy temperature, sap flow, and stem diameter variation (SDV), among other variables, have proved useful not only for research purposes, but also for precise irrigation scheduling in commercial orchards. In this work we focus on the use of SDV records for irrigation scheduling. Of those mentioned above, this is the water-stress indicator that has received most attention from the scientific community, in terms of its potential for irrigating commercial orchards. Apart from being capable of an early detection of water stress, even if this is mild, SDV can be continuously and automatically recorded. This is a clear advantage over conventional indicators such as stem water potential (Ψ_{stem}). Among the SDV-derived indices that are useful for scheduling irrigation, the maximum daily shrinkage (MDS) and stem growth rate (SGR) are the most widely used. For young trees, and in periods of rapid stem growth, SGR could be a better indicator than MDS. In periods of negligible growth, however, SGR cannot be used as an indicator of plant water stress. Considerable differences in both MDS and SGR as a function of crop load have been reported for some species. It has been found, that SDV outputs are affected by seasonal growth patterns, crop load, plant age and size, and other factors, apart from water stress. Thus, expert interpretation of SDV records is required before using them for scheduling irrigation, which limits their potential for automating the calculation of the irrigation dose. For some species, the MDS vs Ψ_{stem} relationships show diurnal hysteresis and seasonal changes. Some relationships also shown an increase of MDS as the plant water potential fell to a certain value, after which MDS decreases as the plant water potential became more negative. This has been reported for peach, lemon, grapevine and olive, among other species. Although SDV-derived indices show a high plant-to-plant variability, in most cases the signal intensity is high enough to achieve an acceptable sensitivity, which, for peach, lemon and pepper has been found to greater than that of Ψ_{stem} and leaf conductance (g_l). In plum, apple and grapevine, however, Ψ_{stem} is more sensitive than MDS and SGR. In any case, the usefulness of an SDV-derived index for irrigation scheduling must be evaluated for the orchard conditions. In this work we describe the qualities that must be considered in such evaluation. One of them, the signal intensity, is being successfully used to schedule low-frequency irrigation in orchards of a variety of species, for both full- and deficit-irrigation treatments. When combined with aerial or satellite imaging, SDV measurements are useful for scheduling irrigation in large orchards with high crop-water-stress variability.

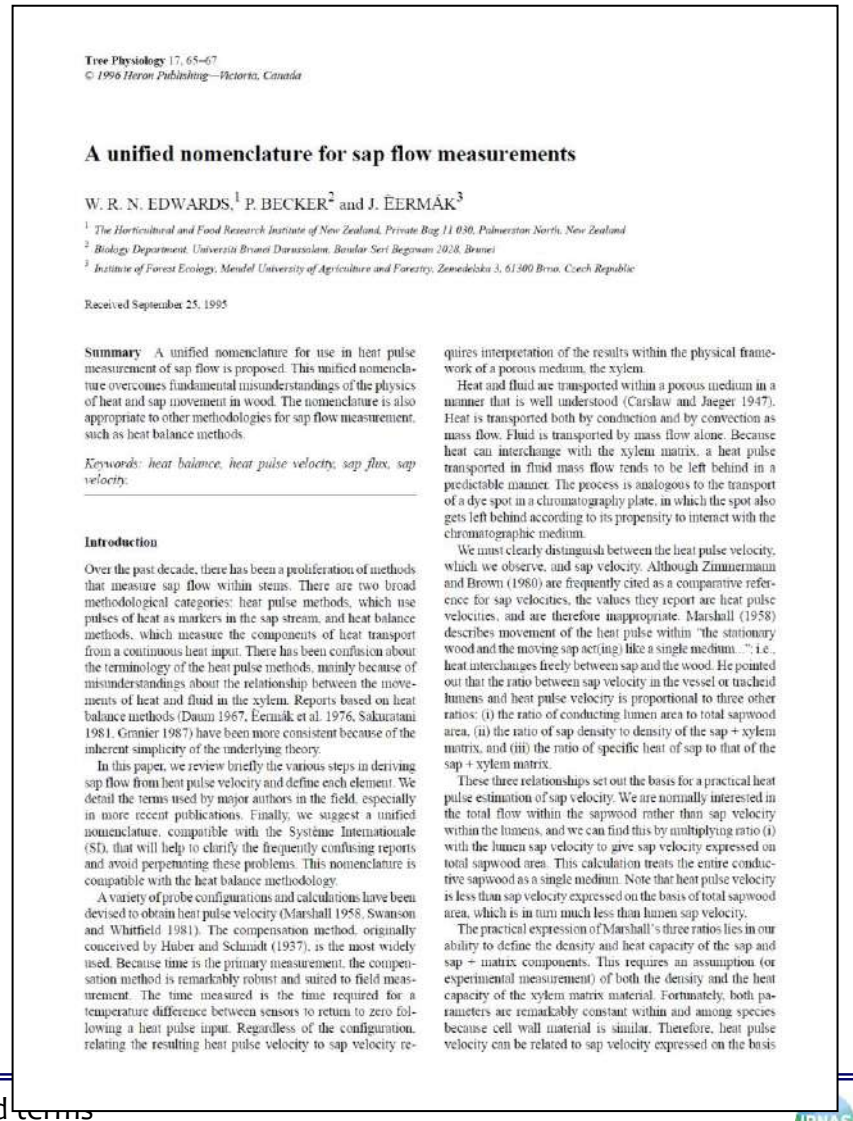
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0168-1923/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.agrformet.2009.11.006



Tree Physiology 17, 65–67
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A unified nomenclature for sap flow measurements

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Received September 25, 1995

Summary A unified nomenclature for use in heat pulse measurement of sap flow is proposed. This unified nomenclature overcomes fundamental misunderstandings of the physics of heat and sap movement in wood. The nomenclature is also appropriate to other methodologies for sap flow measurement, such as heat balance methods.

Keywords: heat balance, heat pulse velocity, sap flux, sap velocity.

Introduction

Over the past decade, there has been a proliferation of methods that measure sap flow within stems. There are two broad methodological categories: heat pulse methods, which use pulses of heat as markers in the sap stream, and heat balance methods, which measure the components of heat transport from a continuous heat input. There has been confusion about the terminology of the heat pulse methods, mainly because of misunderstandings about the relationship between the movements of heat and fluid in the xylem. Reports based on heat balance methods (Daum 1967, Čermák et al. 1976, Sakuratani 1981, Granier 1987) have been more consistent because of the inherent simplicity of the underlying theory.

In this paper, we review briefly the various steps in deriving sap flow from heat pulse velocity and define each element. We detail the terms used by major authors in the field, especially in more recent publications. Finally, we suggest a unified nomenclature, compatible with the Système Internationale (SI), that will help to clarify the frequently confusing reports and avoid perpetuating these problems. This nomenclature is compatible with the heat balance methodology.

A variety of probe configurations and calculations have been devised to obtain heat pulse velocity (Marshall 1958, Swanson and Whitfield 1981). The compensation method, originally conceived by Huber and Schmidt (1937), is the most widely used. Because time is the primary measurement, the compensation method is remarkably robust and suited to field measurement. The time measured is the time required for a temperature difference between sensors to return to zero following a heat pulse input. Regardless of the configuration, relating the resulting heat pulse velocity to sap velocity requires interpretation of the results within the physical framework of a porous medium, the xylem.

Heat and fluid are transported within a porous medium in a manner that is well understood (Carslaw and Jaeger 1947). Heat is transported both by conduction and by convection as mass flow. Fluid is transported by mass flow alone. Because heat can interchange with the xylem matrix, a heat pulse transported in fluid mass flow tends to be left behind in a predictable manner. The process is analogous to the transport of a dye spot in a chromatography plate, in which the spot also gets left behind according to its propensity to interact with the chromatographic medium.

We must clearly distinguish between the heat pulse velocity, which we observe, and sap velocity. Although Zimmermann and Brown (1980) are frequently cited as a comparative reference for sap velocities, the values they report are heat pulse velocities, and are therefore inappropriate. Marshall (1958) describes movement of the heat pulse within "the stationary wood and the moving sap act(ing) like a single medium..."; i.e., heat interchanges freely between sap and the wood. He pointed out that the ratio between sap velocity in the vessel or tracheid lumens and heat pulse velocity is proportional to three other ratios: (i) the ratio of conducting lumen area to total sapwood area, (ii) the ratio of sap density to density of the sap + xylem matrix, and (iii) the ratio of specific heat of sap to that of the sap + xylem matrix.

These three relationships set out the basis for a practical heat pulse estimation of sap velocity. We are normally interested in the total flow within the sapwood rather than sap velocity within the lumens, and we can find this by multiplying ratio (i) with the lumen sap velocity to give sap velocity expressed on total sapwood area. This calculation treats the entire conductive sapwood as a single medium. Note that heat pulse velocity is less than sap velocity expressed on the basis of total sapwood area, which is in turn much less than lumen sap velocity.

The practical expression of Marshall's three ratios lies in our ability to define the density and heat capacity of the sap and sap + matrix components. This requires an assumption (or experimental measurement) of both the density and the heat capacity of the xylem matrix material. Fortunately, both parameters are remarkably constant within and among species because cell wall material is similar. Therefore, heat pulse velocity can be related to sap velocity expressed on the basis

use of concepts and terms

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The scientific language

3. Precision — Be precise without been wordy.

PRECISE?	PRECISE!
from a nearby weather station	*from a weather station located at 400 m*
clear differences were found	*significant differences were found*
The yearly average precipitation was 500.1 mm	*The yearly average precipitation was 500.1 mm (period 1971-2009)*
Trunk diameter was ca. 40 mm on average	*Trunk diameter was 40.3 ± 2.1 mm (n = 26)*

Fluency is important. If you are bound to provide many data to be precise, consider including them in a table or similar.

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The scientific language

In addition to CLEAR, RIGUROUS and PRECISE, the article must be CONCISE and EASY TO READ:
Focus on the most important information and be FLUENT.

The KISS rule: Keep It Short & Simple

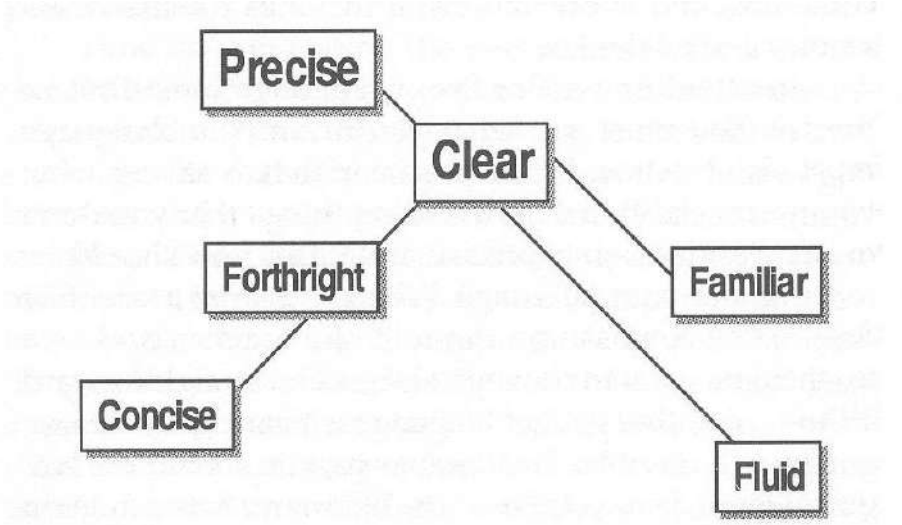


Figure 1-1. Six goals of language in scientific writing. Precision and clarity are the most important.

SOURCE: *The Craft of Scientific Writting*, by Michael Alley

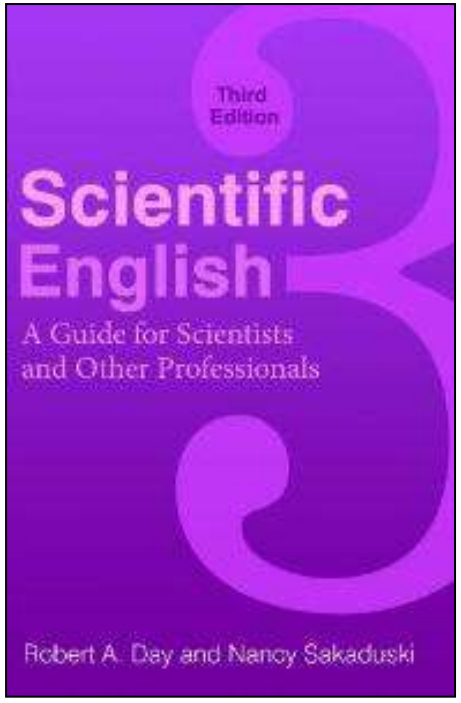
A badly written article has less chances of being published.

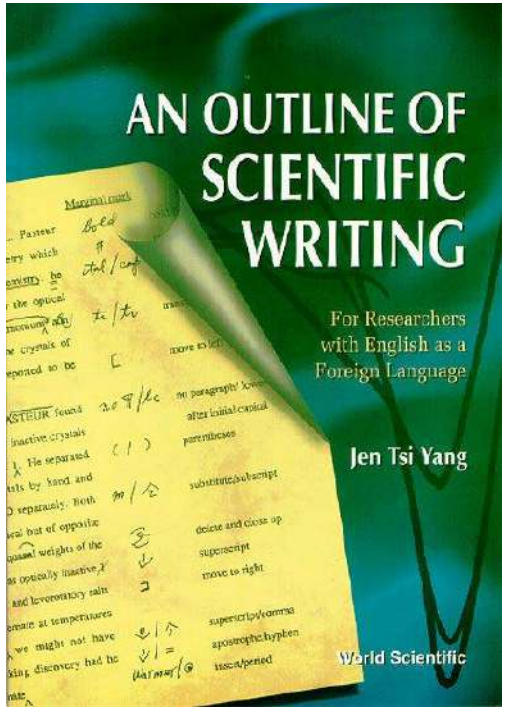
And, if published, the reader will think that the science behind is poor.

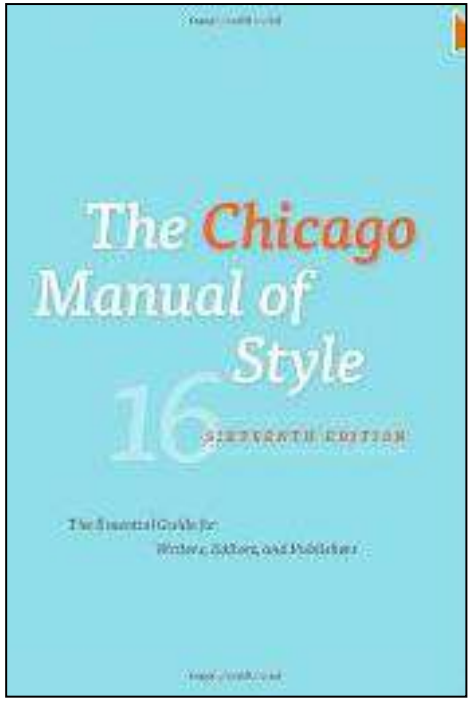
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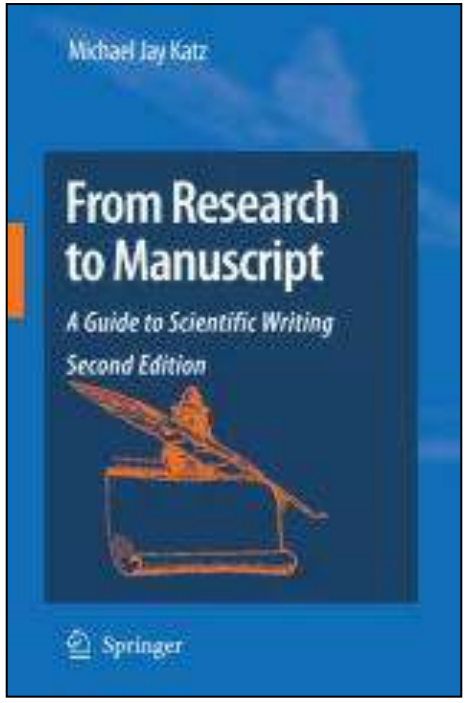
The scientific language

There are good books on the topic: use them.







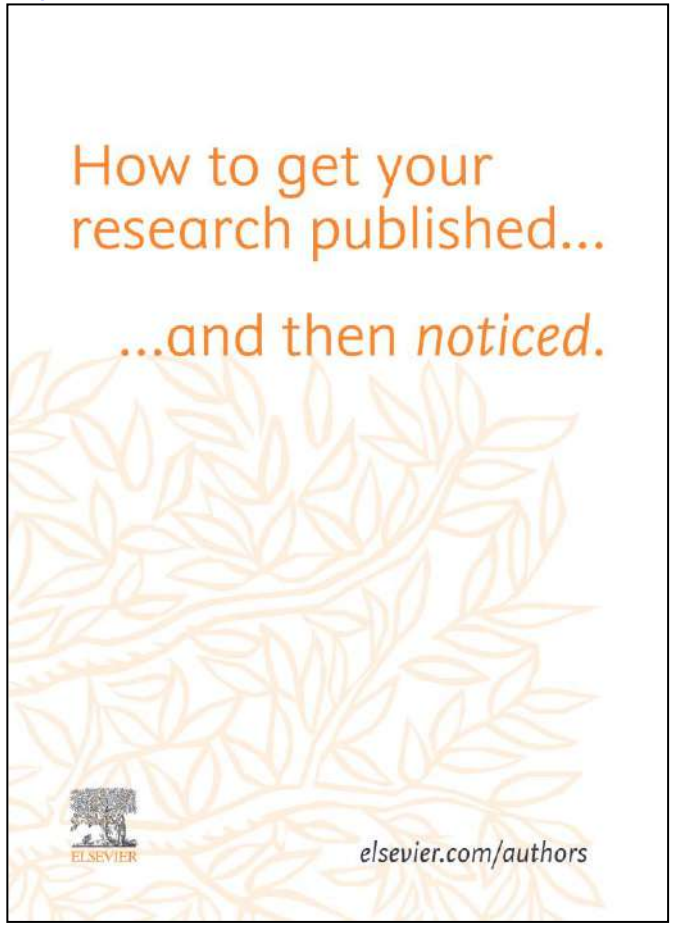


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The scientific language

There are also many websites on academic writing: choose them wisely.

https://www.elsevier.com/?a=91173



www.sfedit.net



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The scientific language

Can we use AI for improving the writing of our manuscripts?

Declaration of generative AI in scientific writing

Authors must declare the use of generative AI in scientific writing upon submission of the paper. The following guidance refers only to the writing process, and not to the use of AI tools to analyse and draw insights from data as part of the research process:

- Generative AI and AI-assisted technologies should only be used in the writing process to improve the readability and language of the manuscript.
- The technology must be applied with human oversight and control and authors should carefully review and edit the result, as AI can generate authoritative-sounding output that can be incorrect, incomplete or biased. Authors are ultimately responsible and accountable for the contents of the work.
- Authors must not list or cite AI and AI-assisted technologies as an author or co-author on the manuscript since authorship implies responsibilities and tasks that can only be attributed to and performed by humans.

The use of generative AI and AI-assisted technologies in scientific writing must be declared by adding a statement at the end of the manuscript when the paper is first submitted. The statement will appear in the published work and should be placed in a new section before the references list. An example:

Policy for authors on the use of generative AI (Elsevier)

https://www.elsevier.com/about/policies-and-standards/publishing-ethics#4-duties-of-authors

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The relevance of a proper use of concepts and terms

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Definitions related to irrigation

We speak of IRRIGATION METHOD when referring to whether we use localized irrigation, sprinkling, furrow, etc., i.e. the expression irrigation method refers to the way in which we apply water.

Do not confuse it with IRRIGATION SYSTEM. This refers to the bombs, pipes, filters, etc., i.e. to all the physical components we use to apply water with the chosen irrigation method.

The IRRIGATION REGIME is determined by the rate, number and time of water applications to crops. It depends on the plant characteristics as well as weather, soil, and hydrologic conditions of irrigated lands. The irrigation regime is the result of the applied irrigation strategy.

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Definitions related to irrigation

The term IRRIGATION STRATEGY refers to both how much water we are going to apply and the timing of irrigation.

If we use **Full Irrigation**, it means we are going to replace the water demanded by the crop with frequent irrigation events (usually daily, in case of localized irrigation).

The alternative to full irrigation is **Deficit Irrigation**. Several deficit irrigation strategies have been defined: supplementary or complementary irrigation, low frequency irrigation, sustained deficit Irrigation, regulated deficit irrigation, partial root zone drying…

IRRIGATION SCHEDULING refers to the calculation of the amount of water to be applied in each irrigation event, and on when to apply it. There is a variety of irrigation scheduling methods, based on soil water, atmospheric demand and/or plant-based measurements.

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Definitions related to irrigation

An EMPIRICAL approach refers to a method of inquiry that relies on observation, experimentation, and evidence, rather than on theory or pure logic. It involves gathering data through direct observations, but the fundamentals of the phenomena behind have not been identified.

A MECHANISTIC approach is a method of understanding phenomena by breaking them down into their fundamental parts and analyzing the interactions among these parts.

The simulation models, for instance, can be mechanistic or empirical. The first are based on observing the response of a variable to an input (e.g. production vs. water applied). The latter are based on understanding the processes that relates production with water applied, and 'mathematizing' them, i.e. describing the equations that regulate those processes.

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Definitions related to irrigation

Do not talk of IRRIGATION TREATMENTS if you consider a rainfall treatment (also referred to as dray-farming treatment). In this case you should talk of WATER TREATMENTS.

Do not use treatments with water supplies greater than ET_c, e.g. 125 % ET_c. They are conceptually wrong.

Do not confuse rainfall with precipitation. Precipitation includes any form of water supply from the atmosphere: Rainfall, snow, hail, dew…

When showing the time course of irrigation in a graph, do not use Julian days. Better DOY (day of year).

The Julian Calendar was introduced by Julius Caesar in 46 BC.
The Gregorian calendar was introduced by Pope Gregory XIII in 1582,
year in which countries like Spain, Portugal and Italy adopted it.
But in Protestant and Orthodox countries it was adopted much later
(in 1923 in Greece).

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Definitions related to irrigation

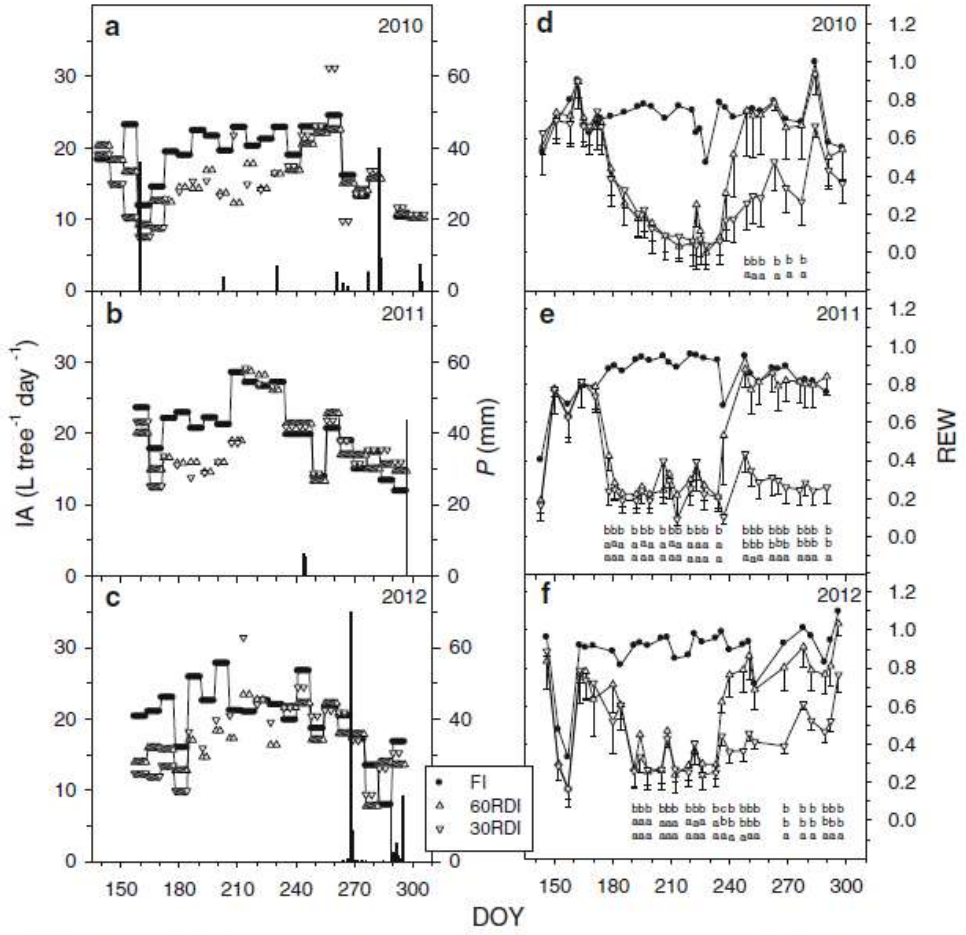
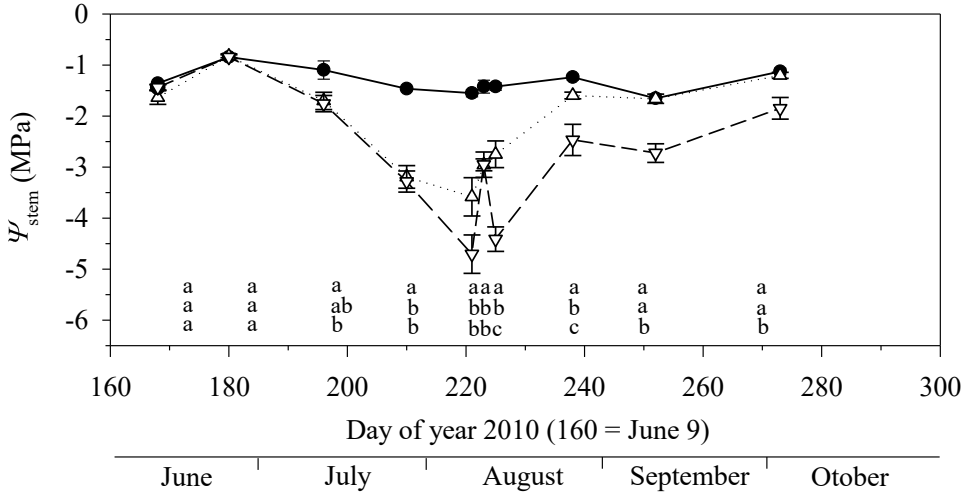
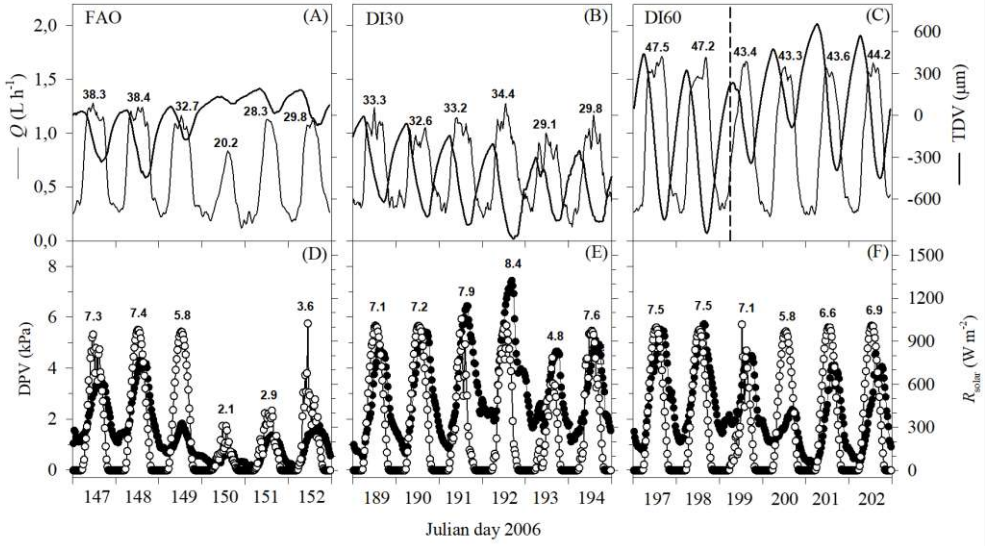


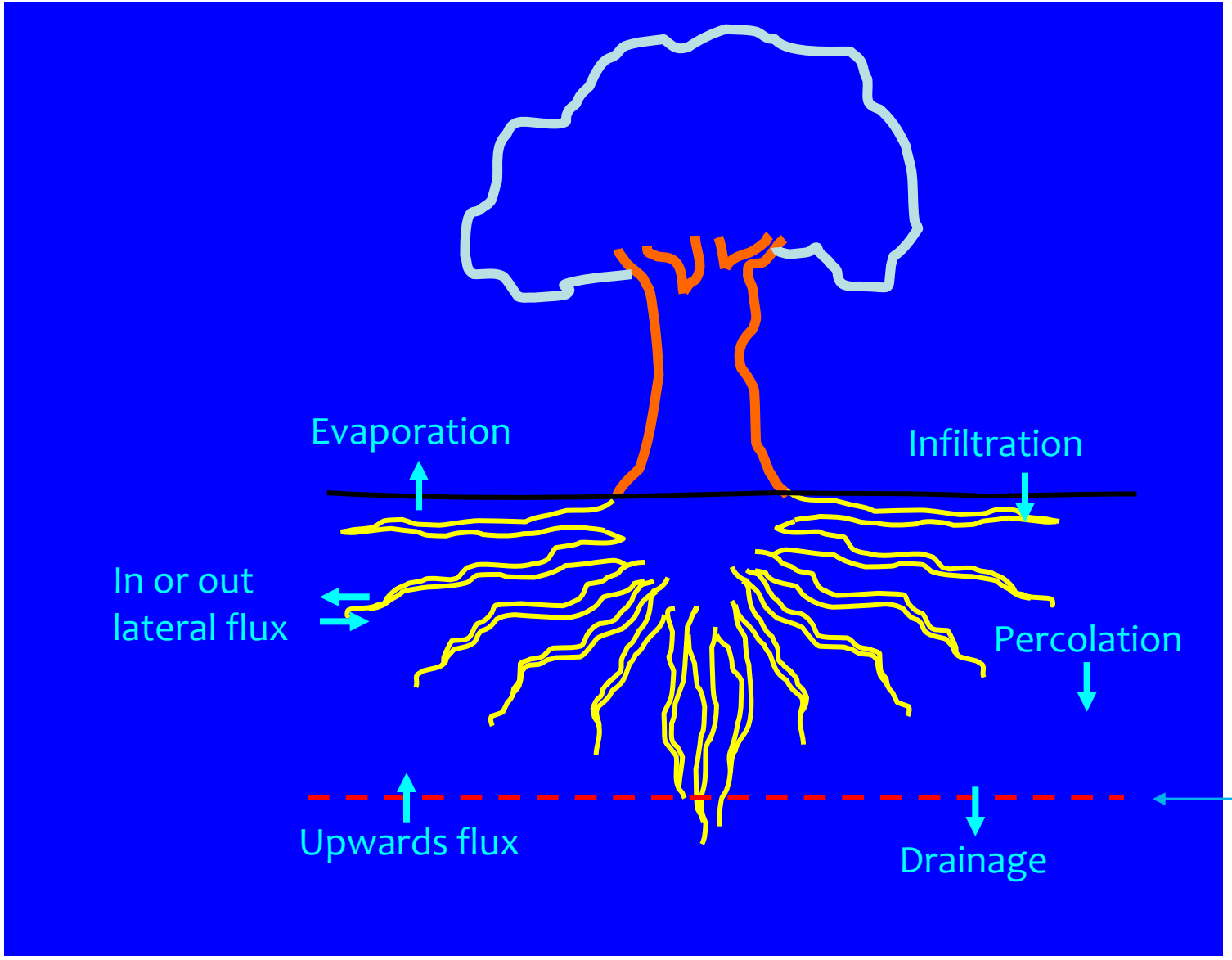
Fig. 3 Seasonal courses both of the irrigation amount (IA) supplied to the each treatment and precipitation (*P*) collected in the orchard (a,b,c). The seasonal courses of the relative extractable water (REW) derived from the soil water contents measured in the plots of each treatment are also shown (d,e,f). Different *letters* indicate significant differences between treatments, at $p<0.05$. *Letters* are not shown when no differences were found. REW values for the FI treatment in 2010 were not considered in the statistical analysis because they correspond to one plot only. DOY = day of year (For 2010 and 2011, DOY 150 = May 30; for 2012, DOY 150 = May 29)





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Soil water movement



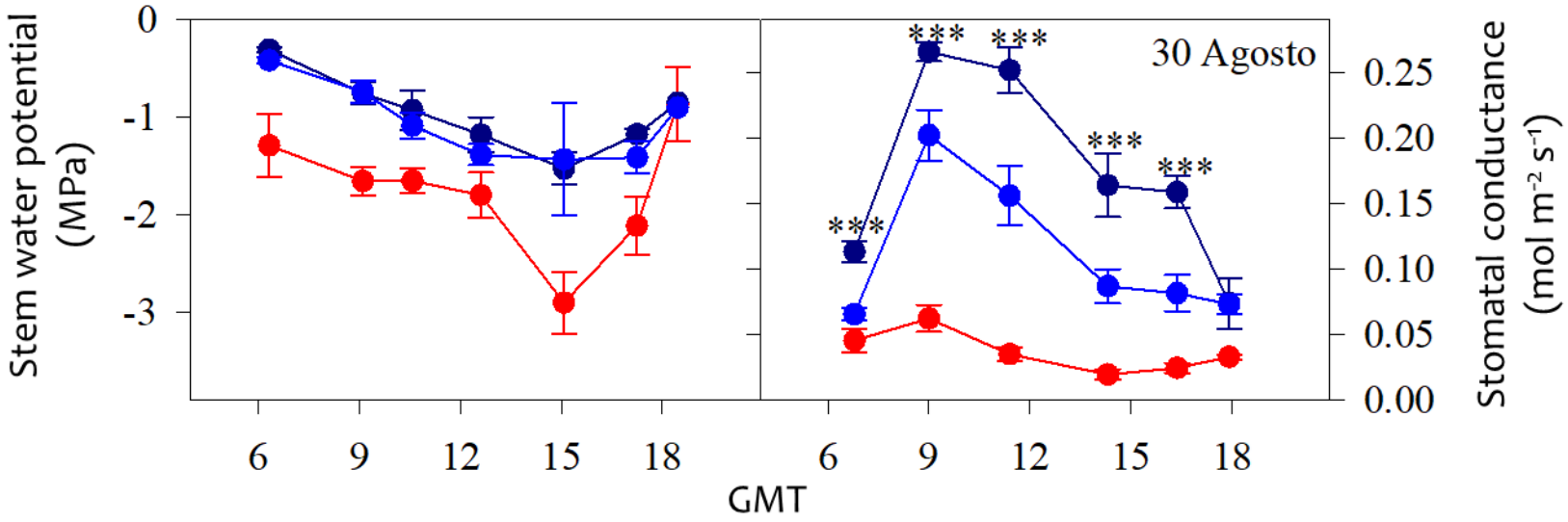
Some use “deep percolation” as synonymous of “drainage”. It is not recommended.

The considered soil profile (with or without roots)

“Effective” rooting depth

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Isohydric vs anisohydric behaviour



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Isohydric vs anisohydric behaviour

We can find in the literature comments like this one:

> In anisohydric plants (barley, sunflower) Ψ_{leaf} markedly decreases with decreasing soil water availability or increasing evaporative demand. By contrast, the isohydric plants (maize, sugarcane, laurel) keep their Ψ_{leaf} above a certain threshold regardless or soil water availability or atmospheric demand (Schultz, 2003; Lovisolo et al., 2010).

But we must bare in mind that a particular species can show an anisohydric or isohydric behaviour, depending on conditions.

> Lovisolo et al. (2010): The same cultivar can behave as iso- or anisohydric, depending on the conditions. For instance, 'Pinot noir' behaves as anisohydric when water stress is applied *pre-véraison* and as isohydric when it is applied *post-véraison* (Poni et al., 1993).

Schultz HR (2003) Differences in hydraulic architecture account for near isohydric and anisohydric behaviours of two field-grown *Vitis vinifera* L. cultivars during drought. *Plant, Cell & Environment* 26, 1393–1405

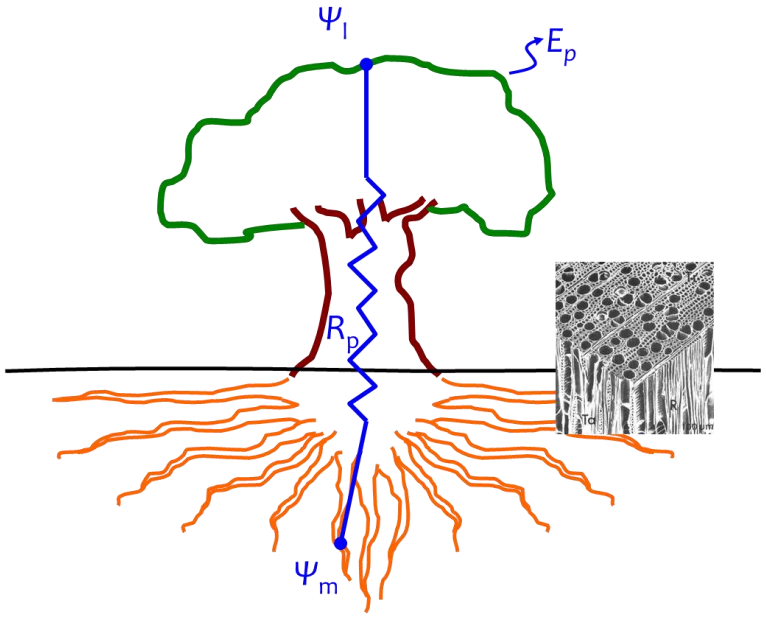
C. Lovisolo et al., 2010. Drought-induced changes in development and function of grapevine (*Vitis* spp.) organs and in their hydraulic and non-hydraulic interactions at the whole-plant level: a physiological and molecular update. *Functional Plant Biology*, 2010, 37, 98–116

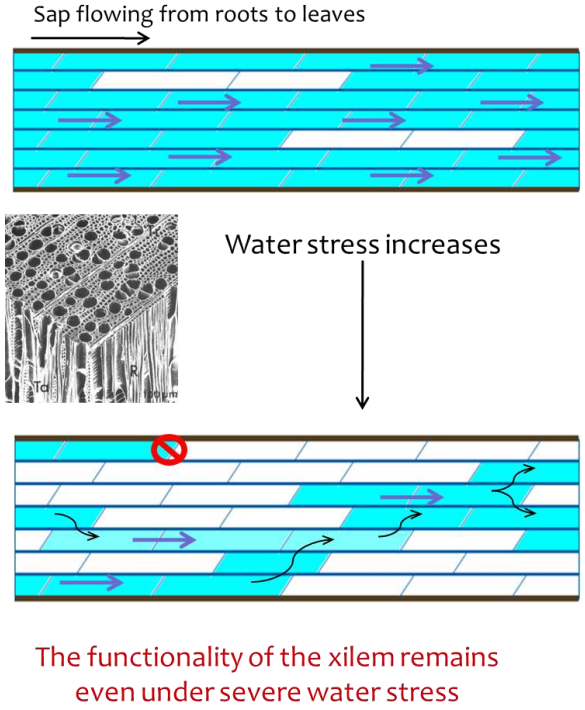
S. Poni et al. (1993) The effects of pre- and postveraison water stress on growth and physiology of potted *Pinot Noir* grapevines at varying crop levels. *Vitis* 32, 207–214.

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Embolism vs. cavitation

Resistance to cavitation and resistance to embolism are often confused.





The functionality of the xilem remains even under severe water stress

Cavitation is the phenomenon in which the static pressure of water in the xylem vessel reduces to below the water's vapour pressure, leading to the formation of small vapor-filled cavities in the liquid.

Embolism refers to the blockage of xylem vessels due to the formation of air bubbles (or gas bubbles).

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Resistance vs. tolerance

Resistance: Implies mechanisms or traits that favour the avoidance or escape from stress.

Tolerance: Implies mechanisms or traits that favor to limit or repair the damage caused by stress.

To many, drought resistance includes drought tolerance:

drought resistance
- drought avoidance
- drought tolerance
- drought escape
- drought recovery

Drought avoidance: The ability of plants to maintain high tissue water content despite reduced water content in the soil.

Drought tolerance: The ability to maintain leaf area and growth under prolonged water stress.

Drought escape: The ability of a plant species to complete its life cycle before the onset of drought.

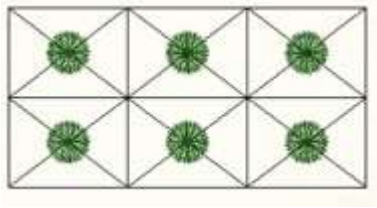
Drought recovery: The ability of a plant to recover from water stress after a period of drought.

R. G. Omprakash et al. (2017). Resistance/Tolerance Mechanism under Water Deficit (Drought) Condition in Plants. Int. J. Curr. Microbiol. App. Sci., 6(4): 66-78.

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Leaf area index

Watch out! The leaf area index (LAI) can be calculated in two different ways:



- LAI as m^2 of leaves per m^2 of soil corresponding to each tree within the orchard
- LAI as m^2 of leaves per m^2 of soil covered by the canopy



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Yield vs. production

Yield: Is the marketable production, i.e. the fraction of the production that the grower can sell.

Production: Includes the yield plus the fraction of the production that cannot be sold because of poor quality, low harvesting efficiency, etc.

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Water use efficiency vs. water productivity

$$\text{Irrigation Efficiency} = \frac{ET_c}{IA} \qquad \frac{m^3\ ha^{-1}}{m^3\ ha^{-1}}$$

$$\text{Water Use Efficiency (WUE)} = \frac{\text{Yield}}{IA + P_e} \qquad \frac{kg}{m^3\ ha^{-1}}$$

Efficiency

$$\frac{\text{used input}}{\text{applied input}}$$

Productivity

$$\frac{\text{obtained output}}{\text{applied input}}$$

$$\text{Water Use Efficiency (WUE)} = \frac{\text{Yield}}{IA + P_e} = \text{Crop water Productivity } (WP_c)$$

The term WUE_c become popular from the 1960s (Viets, 1962), while the use of the term WP_c increased from the early 2000s.

Viets, F.G., Jr. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:223–264.

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Water use efficiency vs. water productivity

✓ $\mathrm{WUE_c} = \frac{\mathrm{ET_c}}{I + P}$

✓ $\mathrm{WUE_i} = \frac{A_\mathrm{N}}{g_\mathrm{s}}$

✗ $\mathrm{WUE_p} = \frac{\mathrm{biomass}}{E_\mathrm{p}}$

✗ $\mathrm{WUE_C} = \frac{\mathrm{biomass}}{\mathrm{ET_C}}$

Water use efficiency (WUE)

$$\frac{\text{total amount of water used}}{\text{total amount of water applied}}$$

dimensionless (%)

Water productivity (WP)

$$\frac{\text{obtained output}}{\text{applied input}}$$

kg m^{-3}

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Water use efficiency vs. water productivity

$$WP_I = \frac{yield}{IWU} \qquad \frac{kg\ ha^{-1}}{m^3 ha^{-1}}$$

$$WP_c = \frac{yield}{TWU}$$

Kijne et al. (2003)

Rodrigues and Pereira (2009)

Pereira et al. (2012)

IWU = amount of water applied by irrigation

TWU = total water involved in crop production

$$TWU = ET_c + LF + N\text{-}BWU$$

Non-beneficial water use: drainage, runoff, evaporation

When referring to WP, you must specify the denominator

Kijne, J.W., Barker, R., Molden, D., 2003. Water productivity in agriculture: limits and opportunities for improvement (Comprehensive Assessment of Water Management in Agriculture Series 1). CABI, Wallingford.
Rodrigues, G.C., Pereira, L.S., 2009. Assessing economic impacts of deficit irrigation as related to water productivity and water costs. Biosys. Eng. 103, 536-551.
Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manage. 108, 39–51.

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The biophysical vs. economic water productivity

Biophysical

$$WP_I = \frac{\text{yield}}{\text{IWU}}$$

$$WP_c = \frac{\text{yield}}{\text{TWU}}$$

kg m^{-3}

IWU = amount of water applied by irrigation

TWU = total water involved in crop production

Economic

$$EWP_I = \frac{\text{Profit}}{\text{IWU}}$$

$$EWP_c = \frac{\text{Profit}}{\text{TWU}}$$

€ m^{-3}

Income from selling the yield

Depreciation
Insurances
Permanent workers
Taxes

Profit = revenues – variable costs - fixed costs – opportunity costs

Raw material
Temporary workers
Machinery use
Energy

Profit of an alternative

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Water use efficiency vs. water productivity

Agricultural Water Management 237 (2020) 106074

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Water use indicators and economic analysis for on-farm irrigation decision: A case study of a super high density olive tree orchard

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Table 1
Definitions of terms related to water use efficiency (WUE), crop water productivity (WP) and economic water productivity (EWP) often used in the literature. The * symbol means that the indicator is not recommended for evaluating the agricultural use of water (see Sections 2.1 for details and 3.3.1 for discussion).

Indicator	Units	Eq. No.	Definition and details
$WUE_c = \frac{ET_c}{I+P}$	$\frac{m^3 ha^{-1}}{m^3 ha^{-1}}$	1	*Crop WUE*: Ratio between the actual crop evapotranspiration (ET_c) and the total water applied by irrigation (I) and precipitation (P). After Perry et al. (2009).
$WUE_i = \frac{A_N}{g_s}$	$\frac{\mu mol\, CO_2\, m^{-2} s^{-1}}{mol\, H_2O\, m^{-2} s^{-1}}$	2	*Intrinsic WUE*: Ratio between the net CO_2 assimilation rate (A_N), or net photosynthesis, and the stomatal conductance (g_s). Measurements are made at the leaf level (in a leaf or a group of leaves), for a short period of time (normally from seconds to minutes). After Osmond et al. (1980).
$*\ WUE_p = \frac{biomass}{Ep}$	$\frac{kg\, plant^{-1}}{m^3 plant^{-1}}$	3	*Plant WUE*: Ratio between total biomass produced by a plant along the growing season and the total amount of water transpired by the plant in the same period (E_p). After Viets (1962) and Flexas et al. (2010).
$*\ WUE_c = \frac{biomass}{ET_c}$	$\frac{kg\, ha^{-1}}{m^3 ha^{-1}}$	4	*Crop WUE*: Ratio between total biomass produced by a crop along the growing season and the total amount of water consumed by the crop, or crop evapotranspiration (ET_c), in the same period. After Viets (1962) and Flexas et al. (2010).
$WP_c = \frac{yield}{ET_c}$	$\frac{kg\, ha^{-1}}{m^3 ha^{-1}}$	5	*Crop Water Productivity*: Ratio between the marketable yield produced by a crop and the water consumed by the crop or crop evapotranspiration (ET_c). Some authors call it "Bio-physical Crop Water Productivity" or "Physical Crop Water Productivity", to differentiate from the Economic Water productivity. After Kijne et al. (2003)
$WP_c = \frac{yield}{TWU}$	$\frac{kg\, ha^{-1}}{m^3 ha^{-1}}$	6	*Crop Water Productivity*: Some authors propose the total amount of water involved in crop production (TWU) as denominator of WP_c (See Section 2.1 for details). After Rodrigues and Pereira (2009).
$WP_I = \frac{yield}{IWU}$	$\frac{kg\, ha^{-1}}{m^3 ha^{-1}}$	7	*Irrigation Water Productivity*: Ratio between the marketable yield produced by a crop along the growing season and the irrigation water applied (IWU) in the same period. After Rodrigues and Pereira (2009).
$GEWP_I = \frac{Gross\ Margin}{IWU}$	$\frac{€\, ha^{-1}}{m^3 ha^{-1}}$	8	*Gross Economic Irrigation Water Productivity*: Ratio between the Gross Margin (revenue-variable costs) (in whatever currency; euros are used in this case) related to a crop along the growing season and the irrigation water applied (IWU) in the same period. See text for details on the Gross Margin.
$NEWP_I = \frac{Net\ Margin}{IWU}$	$\frac{€\, ha^{-1}}{m^3 ha^{-1}}$	9	*Net Economic Irrigation Water Productivity*: Ratio between the Net Margin (revenue – variable and fix costs) (in whatever currency; euros are used in this case related to a crop along the growing season and the irrigation water applied (IWU) in the same period
$EWP_c = \frac{Profit}{TWU}$	$\frac{€\, ha^{-1}}{m^3 ha^{-1}}$	10	*Economic Crop Water Productivity*: Ratio between the Profit (revenue-variable, fix and opportunity costs) (in whatever currency; euros are used in this case) produced by a crop along the growing season and the total amount of water involved in crop production (TWU). See Section 2.1 for details on TWU.
$EWP_I = \frac{Profit}{IWU}$	$\frac{€\, ha^{-1}}{m^3 ha^{-1}}$	11	*Economic Irrigation Water Productivity*: Ratio between the Profit (revenue-variable, fix and opportunity costs) (in whatever currency; euros are used in this case) produced by a crop along the growing season and the irrigation water applied (IWU) in the same period.

Water use efficiency vs. water productivity

IRRIGATION AND DRAINAGE
Irrig. and Drain. (in press)
Published online in Wiley InterScience (www.interscience.wiley.com) **DOI**: 10.1002/ird.323

EFFICIENT IRRIGATION; INEFFICIENT COMMUNICATION; FLAWED RECOMMENDATIONS†

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Agricultural Water Management 98 (2011) 1840–1846
Contents lists available at ScienceDirect
Agricultural Water Management
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Accounting for water use: Terminology and implications for saving water and increasing production

Chris Perry
Co-Editor in Chief, Agricultural Water Management, 17 Storey Court, St John's Wood Road, London NW8 8QX, United Kingdom

1 A Water-productivity Framework for Understanding and Action

David Molden, Hammond Murray-Rust, R. Sakthivadivel and Ian Makin
International Water Management Institute, Colombo, Sri Lanka

© CAB International 2003. *Water Productivity in Agriculture: Limits and Opportunities for Improvement* (eds J.W. Kijne, R. Barker and D. Molden)

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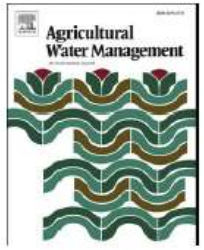
The efficiency of fertilization

Agricultural Water Management 289 (2023) 108547

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat



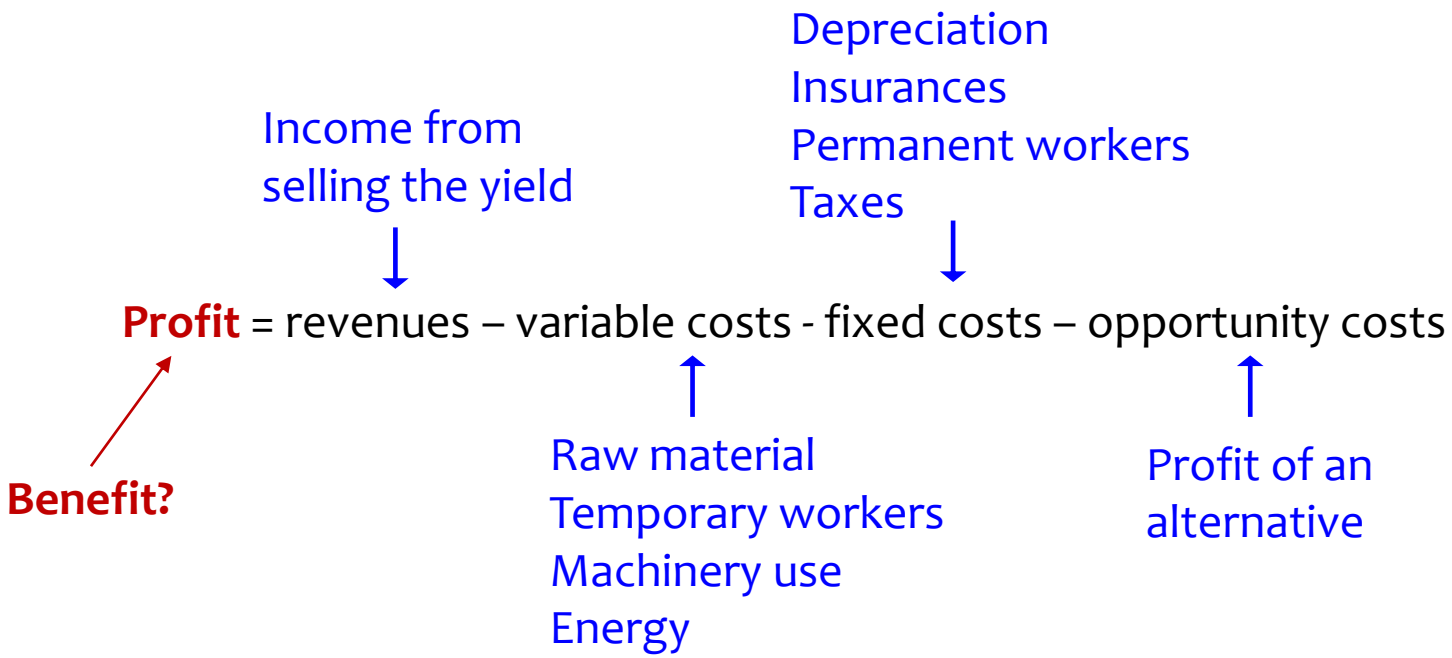
Editorial

Editorial note on terms for soil analyses, nutrient content of fertilizers and Nitrogen Use Efficiency

Rodney Thompson, On behalf of the Editors

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Profit vs. Benefit



If you consider just money, you should use profit.
Benefit refers to something else: money + environmental impact + social improvement….

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The water footprint

Hoekstra (2003) introduced the water footprint (WF) concept to the scientific community.

The WF approach is useful to compare estimated water use per person or in aggregate across countries, as well as to attract the interest of consumers and policy makers on the use of water.

However, many believe that it is inadequate for evaluating the incremental costs, benefits or environmental impacts of water use.

The consumptive WF is divided into a green, a blue and a grey component, which have been defined by the Water Footprint Network (https://waterfootprint.org/en/about-us/).

Green water: precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants.

Blue water: water sourced from surface or groundwater resources, that it is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time.

Grey water: the amount of fresh water required to assimilate pollutants to meet specific water quality standards.

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The “coloured” water

The water footprint and colour schemes used to explain water availability do not always agree with the well established components of the hydrologic cycle, which correct quantification is required for clear distinction between stocks and flows.

Therefore, the water footprint approach could be used at the region/basin/country level, but not at the plot level.



Agricultural Water Management 237 (2020) 106074

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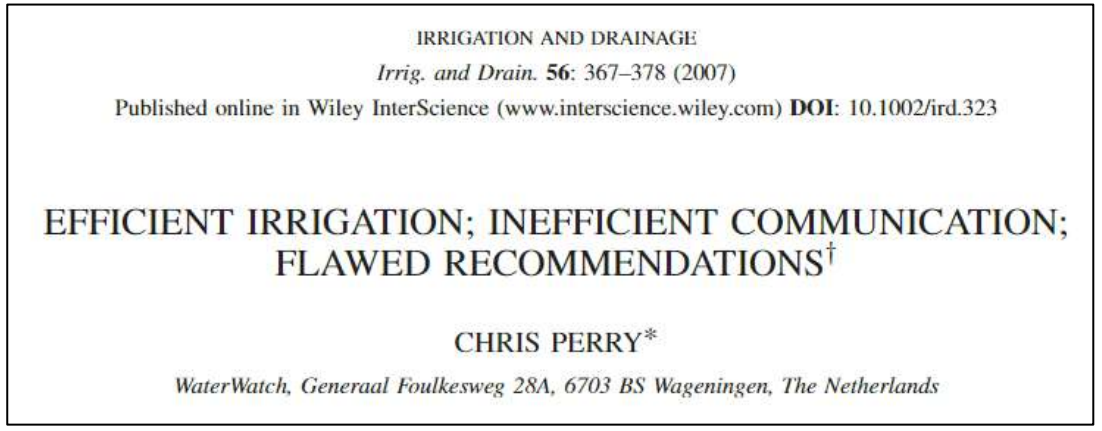
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IRRIGATION AND DRAINAGE

Irrig. and Drain. **56**: 367–378 (2007)

Published online in Wiley InterScience (www.interscience.wiley.com) **DOI**: 10.1002/ird.323

EFFICIENT IRRIGATION; INEFFICIENT COMMUNICATION; FLAWED RECOMMENDATIONS†

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The relevance of a proper use of concepts and terms

1. The scientific language

2. Concepts and terms that are often confused

3. Evapotranspiration

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Evapotranspiration

Reference crop evapotranspiration (ET_{ref}) = Total evaporative water loss, or evapotranspiration, from a standard vegetated surface.

When that surface is grass we use the grass reference evapotranspiration (ET_o), defined as the evapotranspiration of a reference crop with an assumed height of 0.12 m, having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, completely shading the ground, well-watered, and actively growing.

If the vegetated surfaced is alfalfa, for example, we then refer to the alfalfa reference evapotranspiration (ET_r), defined as the evapotranspiration of a reference crop resembling a crop of alfalfa of at least 30 cm of top growth, completely shading the ground, well-watered, actively growing, and standing erect.

The use of other denominations, such as potential evapotranspiration, is strongly discouraged due to ambiguities in their definitions. For more details on definitions, symbols and abbreviations related to evapotranspiration, see Pereira et al. (2015).

Pereira, L.S., Allen, R.G., Smith, M., Raes, D., 2015. Crop evapotranspiration estimation with FAO56: Past and future. Agricult. Water Manag. 147,4–20.

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Evapotranspiration

Values of ET_o can be calculated using different approaches. When the equations from the FAO 56 monograph are used, we refer to the FAO 56 Penman-Monteith (P-M) ET_o, to differentiate from other versions of the P-M equations. The method used to estimate ET_o from meteorological conditions must always be specified, and evidence of the suitability of the chosen method for the specific conditions must be given.

The K_c values given in the FAO 56 monograph are valid only when ET_o is estimated with the FAO56 P-M equation. If other equations are used to estimate ET_o, then the K_c values should be corrected. For instance, if the ASCE-PM, or the Penman equation, are used to estimate ET_o, a conversion factor of 1.15 is required.

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Evapotranspiration

The crop evapotranspiration under standard conditions (ET_c) is the evapotranspiration from a disease-free, well-fertilized crop, growing in large fields, well-watered, and achieving full production under the given climatic conditions. The following equation is used when the crop is under non-limiting growing conditions: $ET_c = K_c\ ET_o$

If there are limiting factors such as poor fertilization, waterlogging or water shortage, salinity or diseases, then ET_c and, in general, the crop performance, are reduced. In this case the recommended equation is

$ET_{c\ act} = K_{c\ act}\ ET_o$,

where $ET_{c\ act}$ is the actual evapotranspiration of the crop under non-standard conditions (Pereira et al, 2021 a,b). Here $K_{c\ act}$, the actual K_c, has a reduced value relative to the standard K_c. Hence the abbreviation ET_a, instead of $ET_{c\ act}$, is valid.

Pereira, L.S., Paredes, P., Hunsaker, D.J., López-Urrea, R., Mohammadi Shad, Z., 2021a. Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. Agricult. Water Manag. 243, 106466.

Pereira, L.S., Paredes, P., López-Urrea, R., Hunsaker, D.J., Mota, M., Mohammadi Shad, Z., 2021b. Standard single and basal crop coefficients for vegetable crops, an update of FAO56 crop water requirements approach. Agricult. Water Manag. 243, 106196.

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Evapotranspiration

The equation $ET_{c\ act} = K_s\ K_c\ ET_o$ is used when $K_{c\ act}$ is calculated as the product of K_c by a stress coefficient (K_s) accounting for the limitation imposed by the limiting factors.

The K_c coefficient represents the combined impact of transpiration and soil evaporation in a single metric. If we want to differentiate between the effect of transpiration and evaporation, then we can use the dual crop-coefficient (K_{cb}), defined as $K_{C\text{-}dual} = K_{cb} + K_e$, where K_{cb} represents crop transpiration, and K_e represents soil-water evaporation.

Details on the dual crop-coefficient, and on other variations of coefficients relating ET_c to ET_o are given by Allen and Pereira (2009) and Pereira et al. (2021a,b,c). We recommend these papers for definitions, symbols and abbreviations on these coefficients.

Allen, R.G., Pereira, L.S., 2009. Estimating crop coefficients from fraction of ground cover and height. Irrig. Sci. 28,17–34.

Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manage. 108, 39–51.

Pereira, L.S., Paredes, P., Hunsaker, D.J., López-Urrea, R., Mohammadi Shad, Z., 2021a. Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. Agricult. Water Manag. 243, 106466.

Pereira, L.S., Paredes, P., López-Urrea, R., Hunsaker, D.J., Mota, M., Mohammadi Shad, Z., 2021b. Standard single and basal crop coefficients for vegetable crops, an update of FAO56 crop water requirements approach. Agricult. Water Manag. 243, 106196.

Pereira, L.S., Paredes, P., Melton, F., Johnson, L., Mota, M., Wang, T., 2021c. Prediction of crop coefficients from fraction of ground cover and height. Practical application to vegetable, field and fruit crops with focus on parameterization. Agric Water Manage. 252, 106663.

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Evapotranspiration

When working with crops that do not fully cover the ground, such as fruit-tree crops, an additional coefficient K_r is required, such that $ET_c = K_r K_c ET_o$. In this equation K_r is a coefficient related to the percentage of ground covered by the crop.

Other authors, however, use K_r for a reduction coefficient depending on other factors than the ground fraction covered by the crop. Paço et al. (2019), for instance, used K_r as a reduction coefficient accounting for the amount of water remaining in the surface soil layer.

Therefore, the meaning of K_r, its value, and the way in which it has been determined, must be specified. Giving a single value for the product of K_c by K_r is not acceptable. The value of each coefficient must be given separately.

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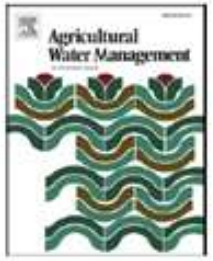
Evapotranspiration

Agricultural Water Management 289 (2023) 108548

Contents lists available at ScienceDirect

Agricultural Water Management

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Editorial

Editorial note on terms for crop evapotranspiration, water use efficiency and water productivity

Enrique Fernández, On behalf of the Editors,

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Institute for Natural Resources and Agrobiology (IRNAS)
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Fundamentals of Irrigation



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Spanish National Research Council (CSIC)

Fundamentals of Irrigation

1. Water in the soil

2. The agrometeorological station

3. Plant-based measurements related to water stress

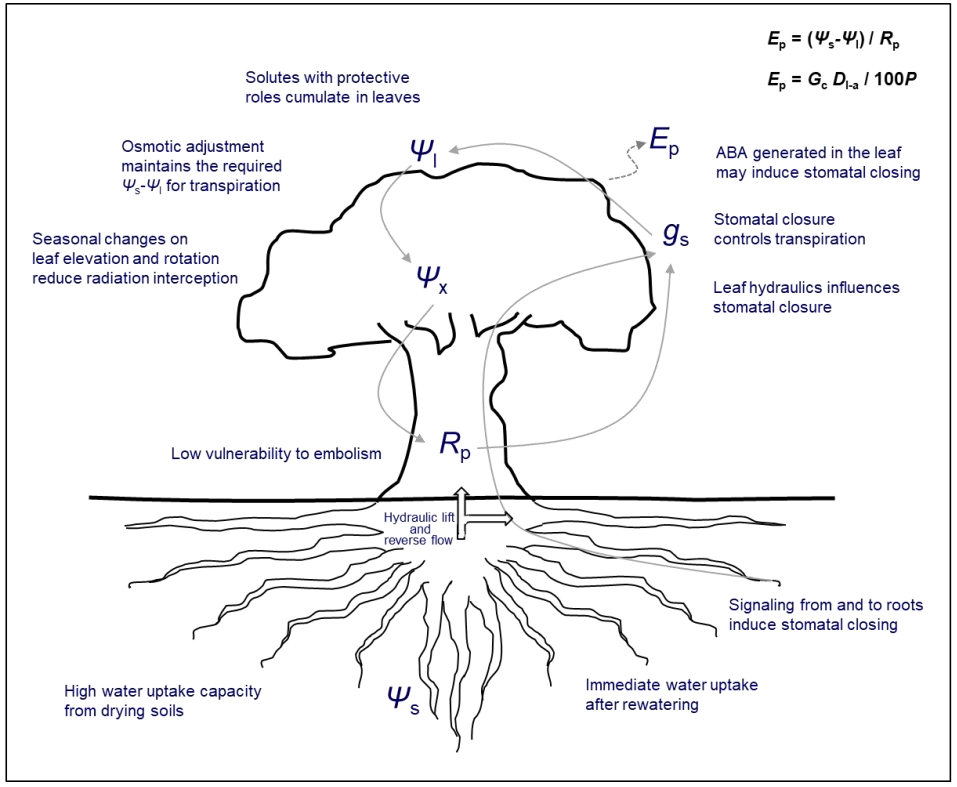
4. Physiological mechanisms related to water stress

5. Agronomic performance

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The Soil-Plant-Atmosphere continuum (SPAC)

The soil–plant–atmosphere continuum (SPAC) describes the continuous water movement from soil via plants to atmosphere.
Some have proposed the term atmosphere–plant–soil continuum (APSC), since water uptake is driven by the atmospheric demand (https://doi.org/10.1016/j.tplants.2020.08.002).



J.-E. Fernández / Environmental and Experimental Botany 103 (2014) 158–179

This means that, to manage irrigation, we need information on variables from the soil, the plant and the atmosphere surrounding the crop.

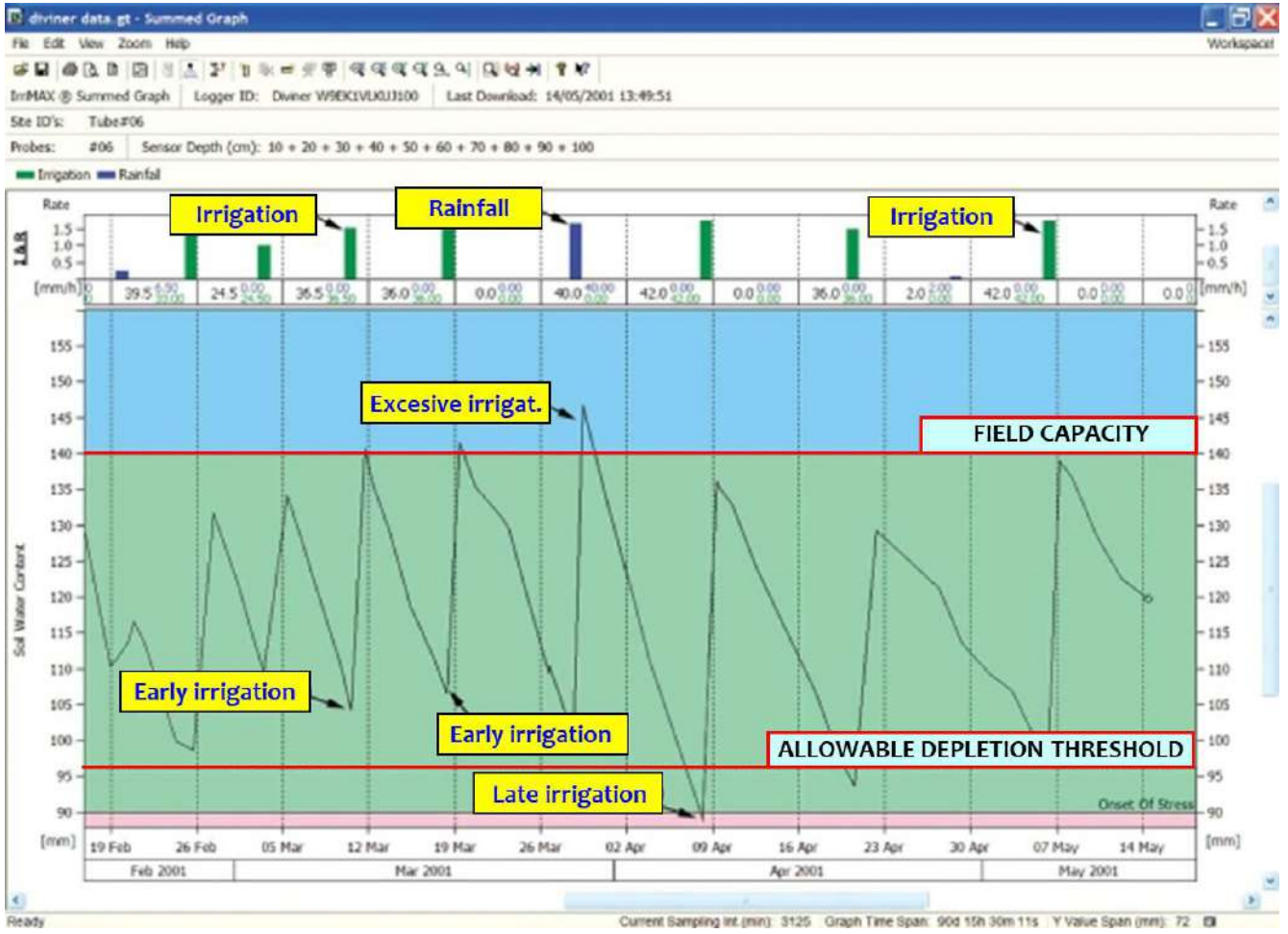
What do we need to know on the soil?

- The soil water status
- Main soil hydraulic characteristics
- The root zone dimensions

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Why soil hydraulic characteristics?

Field capacity, wilting point and hydraulic conductivity are important to manage irrigation.



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The soil water status

1. Amount of water in the soil: Soil water content or soil wetness.

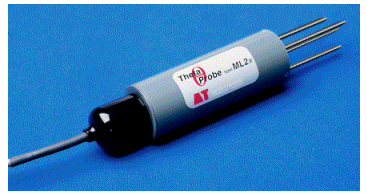
   Volumetric water content

   θ_v $m^3\ m^{-3}$, $cm^3\ cm^{-3}$ or % v/v

   Gravimetric water content

   θ_g $g\ g^{-1}$

$\theta_v = \theta_g \rho_b$ (ρ_b = soil bulk density, $Mg\ m^{-3}$ or $g\ cm^{-3}$)











2. Energy with which the soil retains water: Soil water potential.

$\Psi_s = \Psi_m + \Psi_g + \Psi_o + \Psi_p$

Matric (or presure) potential, or suction

$\Psi_s \approx \Psi_m = h$ cbar or MPa





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The soil water status

1. Amount of water in the soil: Soil water content or soil wetness.

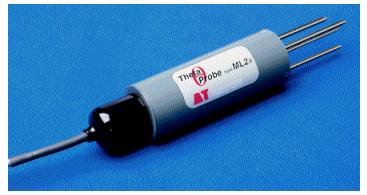
   Volumetric water content

   θ_v $m^3\ m^{-3}$, $cm^3\ cm^{-3}$ or % v/v

   Gravimetric water content

   θ_g $g\ g^{-1}$

$\theta_v = \theta_g \rho_b$ (ρ_b = soil bulk density, $Mg\ m^{-3}$ or $g\ cm^{-3}$)







Diviner 2000



EnviroSCAN



EnviroSMART

2. Energy with which the soil retains water: Soil water potential.

$\Psi_s = \Psi_m + \Psi_g + \Psi_o + \Psi_p$

Matric (or presure) potential, or suction

$\Psi_s \approx \Psi_m = h$ cbar or MPa

1 atmosphere is the weight of a column of water of a base of 1 cm^2 and a height of 1033.6 cm

1 atm = 1033.6 cm of water column

1 atm = 1.03 kg cm^{-2}

1 bar = 1 kg cm^{-2}

1 bar = 100 kPa = 100 cbar

10 bar = 1 MPa

FC -0.01 > Ψ_s > -0.03 MPa = -10 to -30 cbar or kPa

WP -1.5 MPa = -1500 cbar or kPa

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The pF values

The values of Ψ_m, or h, can be expressed as pF values.



$$pF = \log h$$

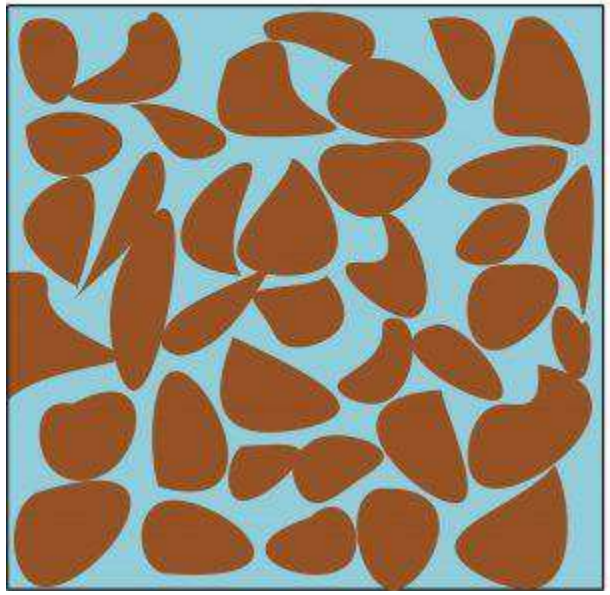
pF	*h* (cm of water)	*H* (cm of Hg)	Soil water status
1	10	0.7	Saturation
2.5	316	23	Field capacity
2.9	800	58.8	Drying soil (limit of the tensiometer)
4.2	15.849	1165.4	Permanent wilting point (it depends on the species)

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Water in the soil

Saturation

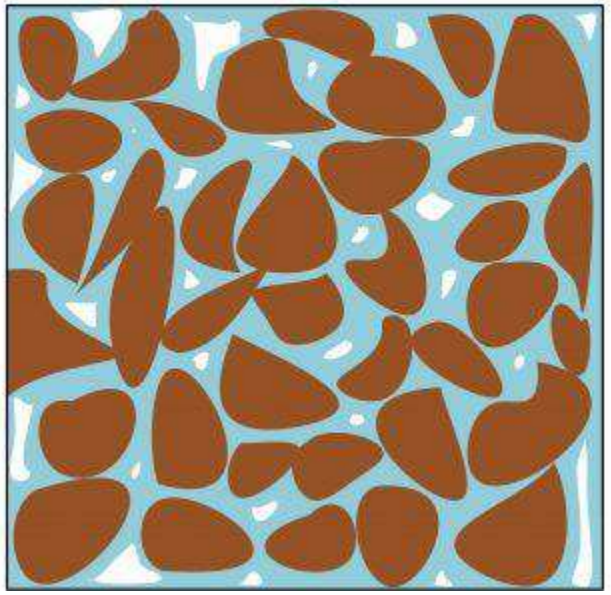
All pores are filled with water



Heavy rainfall or irrigation

Field Capacity

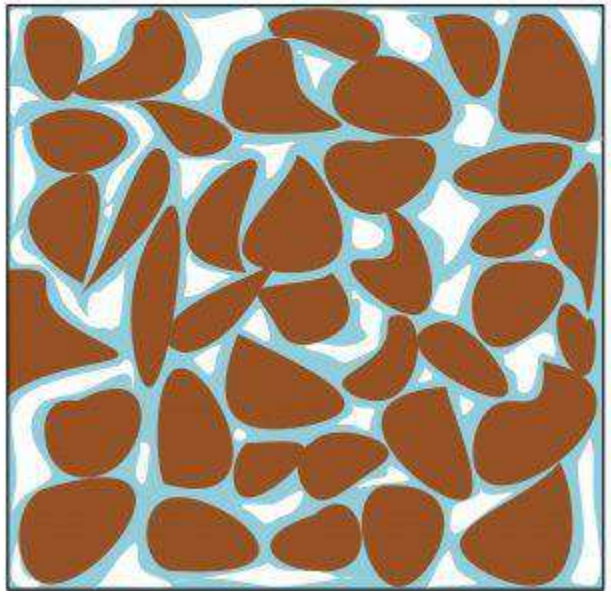
Water in larger pores has drained



Some 24 h later

Permanent Wilting Point

Plants can no longer extract water

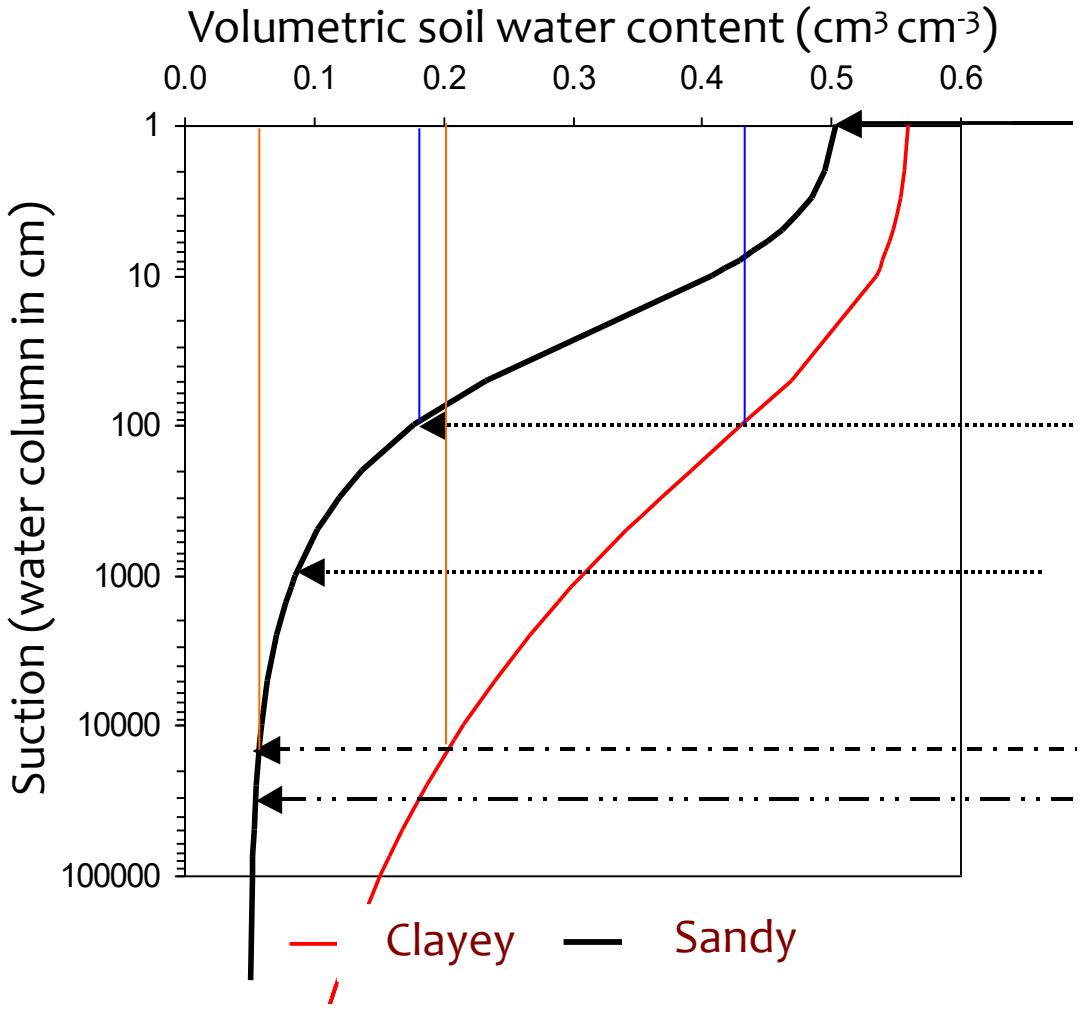


It varies with the species and soil type

SOURCE: Oklahoma Cooperative Extension Service BAR.1537, by S. Datta, S. Taghvaeian ans J. Stivers, June 2017

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The water retention curve



Saturation

Field capacity

Allowable depletion threshold

Wilting point

Dry soil

pF	*h* (cm of water)	*h* (cm of Hg)	Soil water status
1	10	0,7	Saturation
2.5	316	23	Field capacity
2.9	800	58,8	Limit of the tensiometre
4.2	15.849	1165,4	Permanent wilting point (it depends on the species)

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Laboratory vs. Field measurements

Whatch out! Most hydraulic characteristics are meassured in the lab, and this affects the results.





- The sampling procedure alters the soil structure
- The wall of the rings has an impact on the θ_v values measured at different *h*.



FC value determined from lab measurements: θ_v = 0.33 $m^3\ m^{-3}$

value measured in the field: θ_v = 0.28 $m^3\ m^{-3}$

PWP value determined from lab measurements at *h* = -1.5 MPa: θ_v = 0.08 $m^3\ m^{-3}$

But the PWP value of the olive tree occurs at *h* = -2.5 MPa, or less

Laboratory vs. Field measurements

Whatch out! Most hydraulic characteristics are meassured in the lab, and this affects the results.





- The sampling procedure alters the soil structure
- The wall of the rings has an impact on the θ_v values measured at different *h*.

Bagarello V, Provenzano G (1996) Factors affecting field and laboratory measurement of saturated hydraulic conductivity. Transactions of the ASAE, 39, 153-159.

Bao, S (2007) Soil and Agricultural Chemistry Analysis. China Agricultural Press, Beijing, in Chinese with English abstract.

Ferrer F, Pla I, Fonseca, Dalurzo H, Villar JM (2008) Combining field and laboratory methods to calculate soil water content at field capacity and permanent wilting point. In 10th Congress of the European Society for Agronomy. Bologna-Italy. Rivista di Agronomia, 3. 279-280.

Duan X, Xie Y, Liu G, Gao X, Lu H (2010) Field capacity in black soil region, northeast China. Chinese Geogr. Sci. 20, 406-413.

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Pedotransfer functions

The pedotransfer functions (PTF) are used to derive hydraulic properties of the soil from soil data. The PTF Rosetta, for instance, is used to estimate the van Genuchten equation parameters (van Genuchten, 1980). In this equation, used to derive the water retention curve, the relationship between θ_v and Ψ_s is calculated with:

$$\theta(\Psi_s) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\Psi_s|)^n]^m}$$

$\theta(\Psi_s)$ = volumetric water content at matric potential Ψs
θ_r = residual water content
θ_s = saturated water content
α = parameter related to the inverse of the air entry suction (cm^{-1})
n = parameter related to the pore-size distribution
m = 1 − 1 n

Input data:

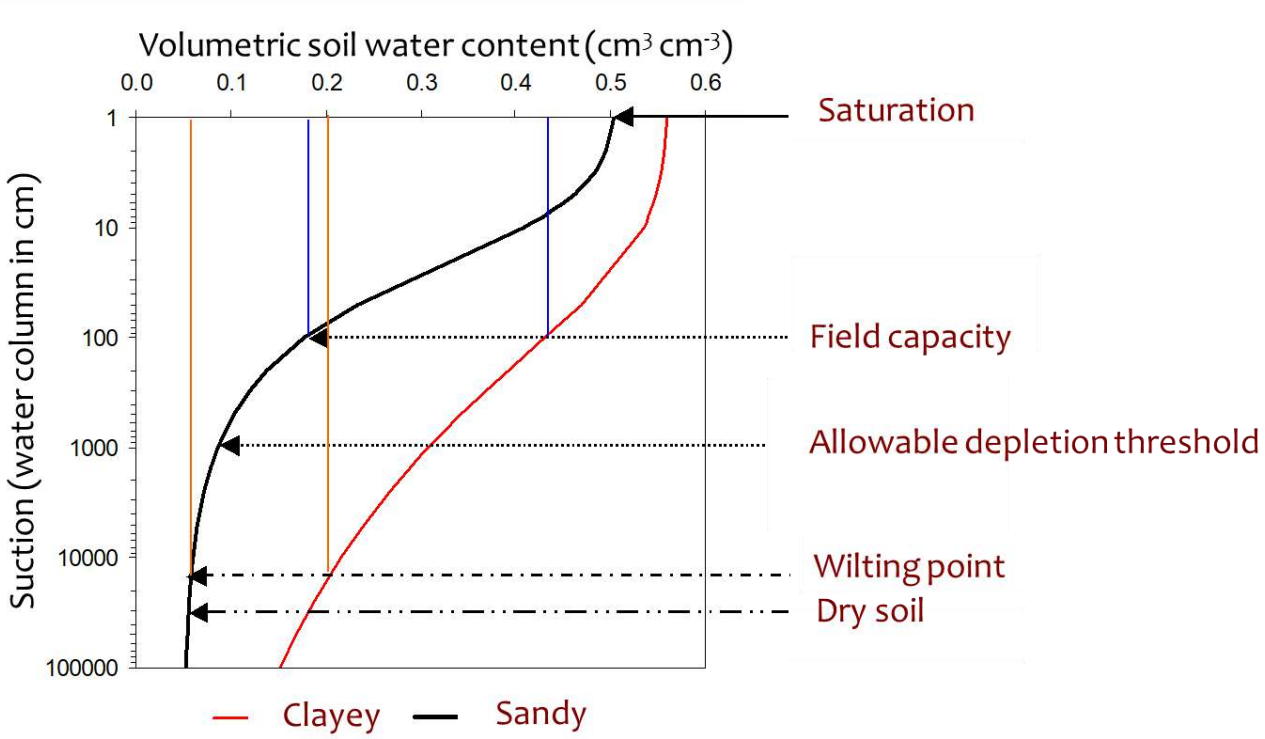
- Soil textural class
- Sand, silt and clay percentages
- Sand, silt and clay percentages and bulk density
- Water retention point at FC and PWP.

Outputs:

- Water retention parameters according to van Genuchten (1980)
- Saturated hydraulic conductivity
- Unsaturated hydraulic conductivity parameters according to van Genuchten (1980) and Mualem (1976)

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Pedotransfer functions



Watch out! Small variations in the input values can lead to large errors at the beginning and at the end of the WRC

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The Rosetta PTF



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Journal of Hydrology 251 (2001) 163–176

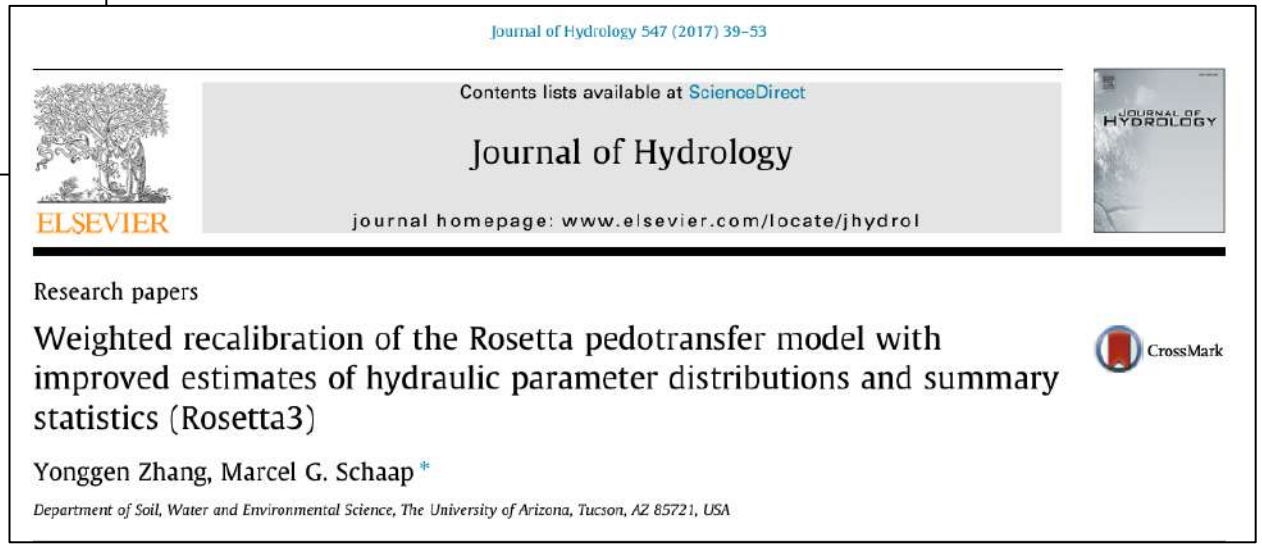
Journal of Hydrology

www.elsevier.com/locate/jhydrol

ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions

Marcel G. Schaap*, Feike J. Leij, Martinus Th. van Genuchten

George E. Brown Jr. Salinity Laboratory, USDA-ARS, 450 W. Big Springs Road, Riverside, CA 92507-4617, USA



Journal of Hydrology 547 (2017) 39–53

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Weighted recalibration of the Rosetta pedotransfer model with improved estimates of hydraulic parameter distributions and summary statistics (Rosetta3)

Yonggen Zhang, Marcel G. Schaap *

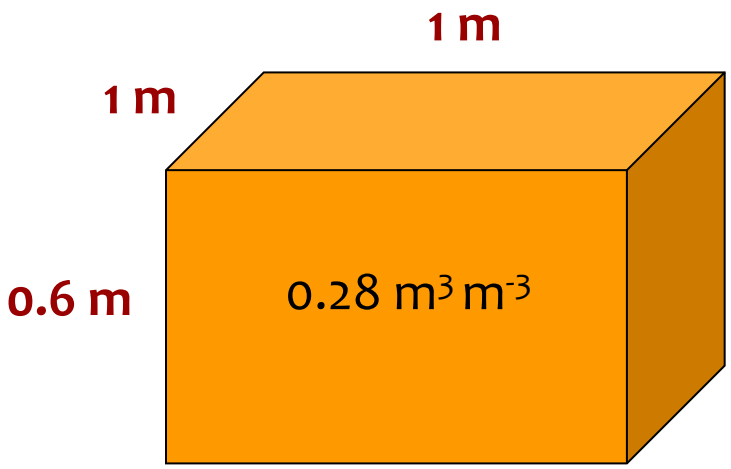
Department of Soil, Water and Environmental Science, The University of Arizona, Tucson, AZ 85721, USA

A **web-based interface** of the Rosetta model developed by Todd Skaggs (USDA-ARS) and Ehsan Ghane (Michigan State University) can be accessed, respectively, by https://www.handbook60.org/rosetta/ and https://dsiweb.cse.msu.edu/rosetta/.

Water stored in the soil

The amount of water stored in the soil depends on both the value of θ_v and the depth of the considered soil profile.

For a crop with a rooting depth of 0.6 m, ¿how much water is stored in the soil if θ_v = 0.28 $m^3\ m^{-3}$ = 0.28 $cm^3\ cm^{-3}$ = 28 % v/v?



1 m x 1 m x 0.6 m = 0.6 m^3

0.6 m^3 x 0.28 $m^3\ m^{-3}$ = 0.163 m^3

0.163 m^3 = 163 L m^{-2} = 163 mm

If the rooting depth is 0.9 m:

1 m x 1 m x 0.9 m = 0.9 m^3

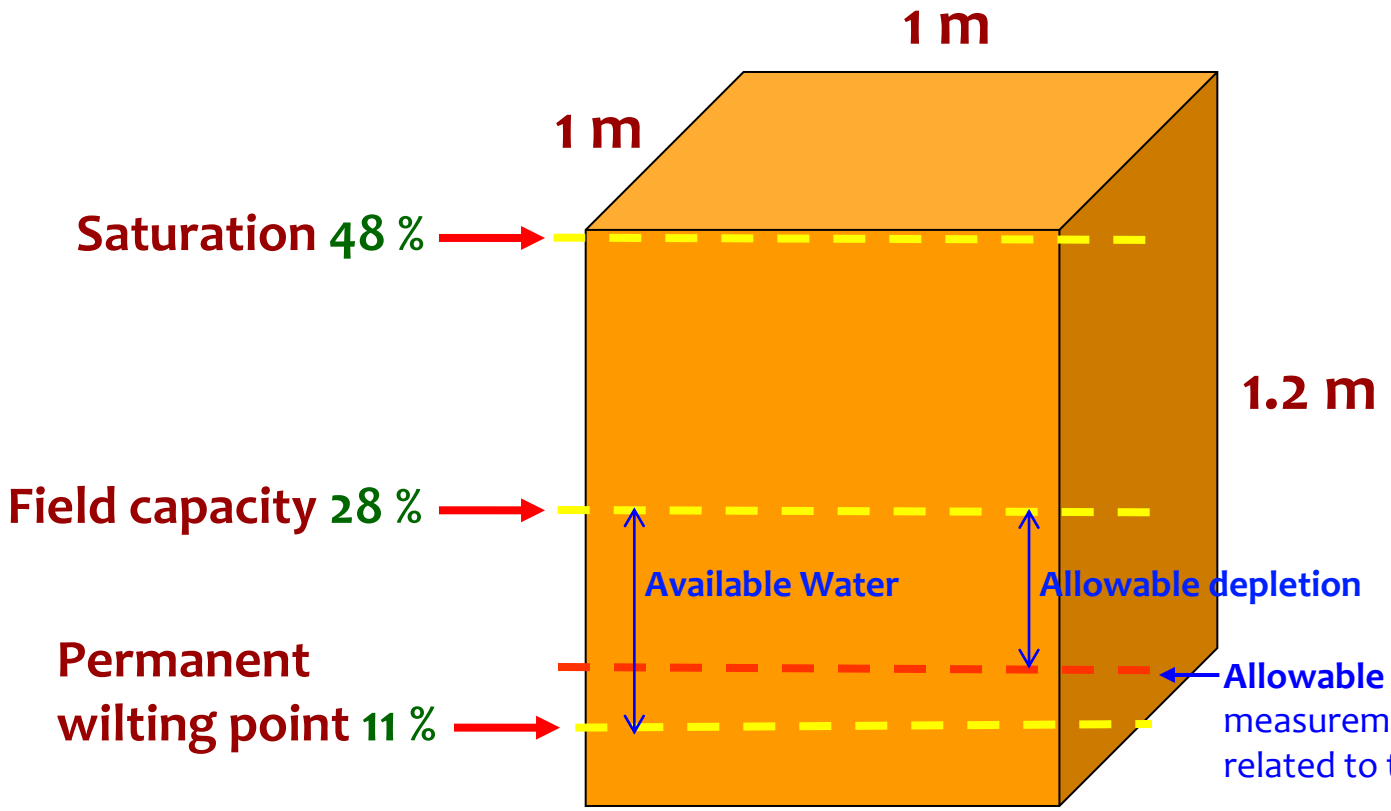
0.9 m^3 x 0.28 $m^3\ m^{-3}$ = 0.252 m^3

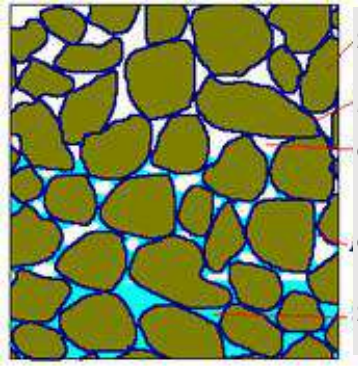
0.252 m^3 = 252 L m^{-2} = 252 mm

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Not all the water stored in the soil is available to the crop

Example for soil for which θ_v at saturation = 0.48 $m^3\ m^{-3}$, θ_v at FC = 0.28 $m^3\ m^{-3}$ and θ_v at WP = 0.11 $m^3\ m^{-3}$





Allowable depletion threshold: To define this value, soil water measurements are contrasted with those of a variable closely related to the crop water stress, e.g. Ψ_{leaf} or Ψ_{stem}

Residual water content, 2-3 %

$AW = (0.28 - 0.11) \times 1200 = 204$ mm

↓

This is the **soil water retention capacity**

The **readily available water** is the amount of water that a plant can consume before reaching the ADT

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Volume and dimensions of the root zone

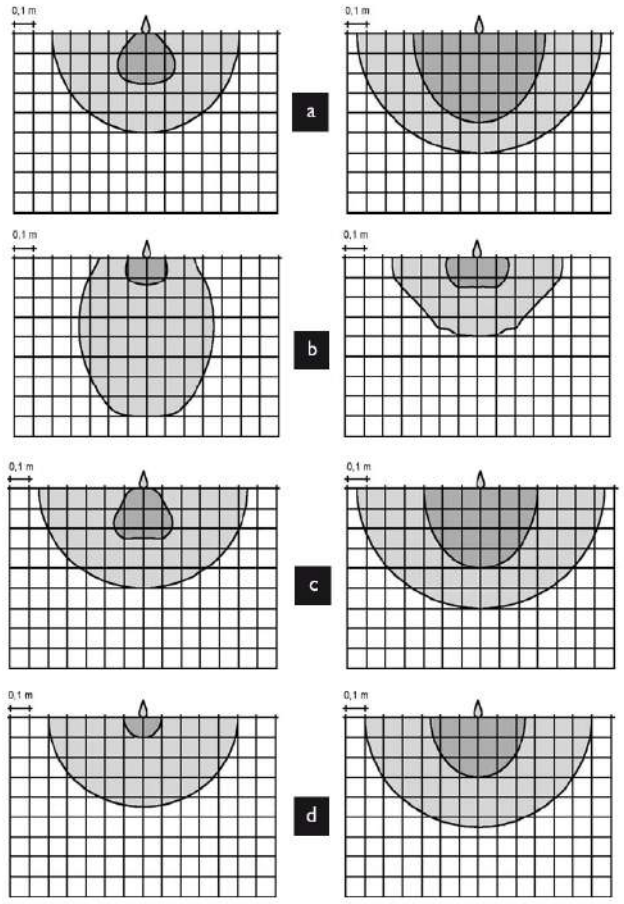


Figura 4. Características de bulbo de riego (zona saturada y zona de influencia) según el Modelo Simdas v.2 (Arbat, 2005), después de una redistribución de 16 h desde que se corta el riego, para goteros y suelos de distintos tipos: a) gotero de 2 L/h (izq) y de 6 L/h (dcha), en un suelo franco, y riego de 3 horas; b) gotero de 4 L/h, en un suelo arenoso (izq) y en uno arcilloso (dcha), y riego de 4 horas; c) gotero de 4 L/h y suelo franco, y riegos de 4 horas (izq) y de 8 horas (dcha); y d) goteros de 4 L/h y riego de 6 horas, en un suelo que inicialmente estaba seco (izq) y otro que inicialmente estaba húmedo (dcha).

You must define the shape and volume of the root zone wetted by irrigation. This can be estimated from visual observations or by using simulation models.



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The root zone has a high impact on the management of irrigation: understanding soil water measurements



Olive trees at 7 m × 5 m, LA = 60 m^2
Water consumption = 1.7 L m^{-2} leaf day^{-1}
θ_v FC = 0.28 $m^3\ m^{-3}$, θ_v PWP = 0.11 $m^3\ m^{-3}$

Root zone volume= 15 m^3

15 x AD = 15 x (0.28 – 0.11) x 0.6 = 1.530 m^3 = 1530 L
1530 / (60 x 1.7) = 15 days before the ADT is achieved



Olive trees at 3.75 m × 1.35 m, LA = 12 m^2
Water consumption = 1.7 L m^{-2} leaf day^{-1}
θ_v FC = 0.28 $m^3\ m^{-3}$, θ_v PWP = 0.11 $m^3\ m^{-3}$

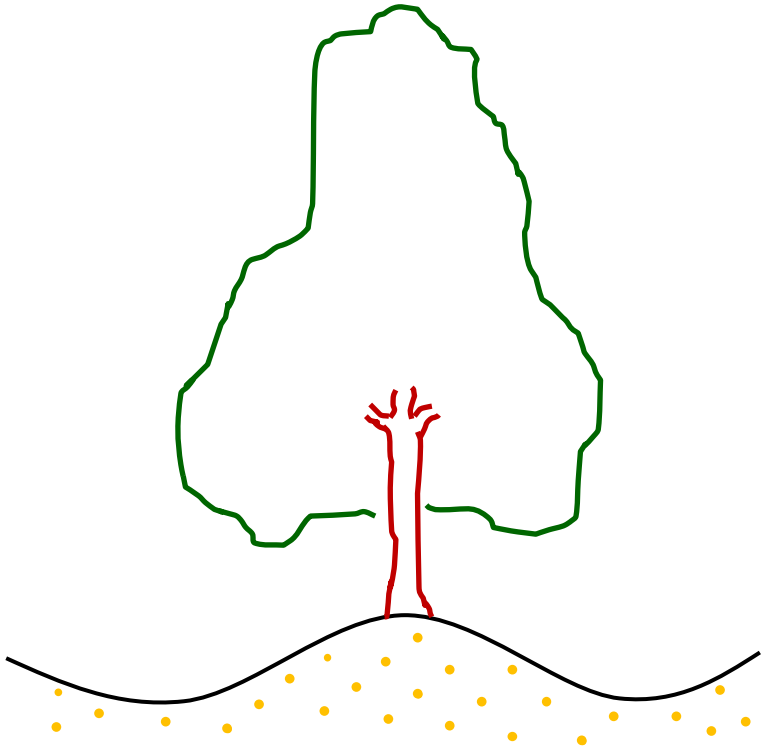
Root zone volume= 1.7 m^3

1.7 x AD = 1.7 x (0.28 – 0.11) x 0.60 = 0.173 m^3 = 173 L
173 / (12 x 1.7) = 8.5 days before the ADT is achieved

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The root zone has a high impact on the management of irrigation: understanding soil water measurements







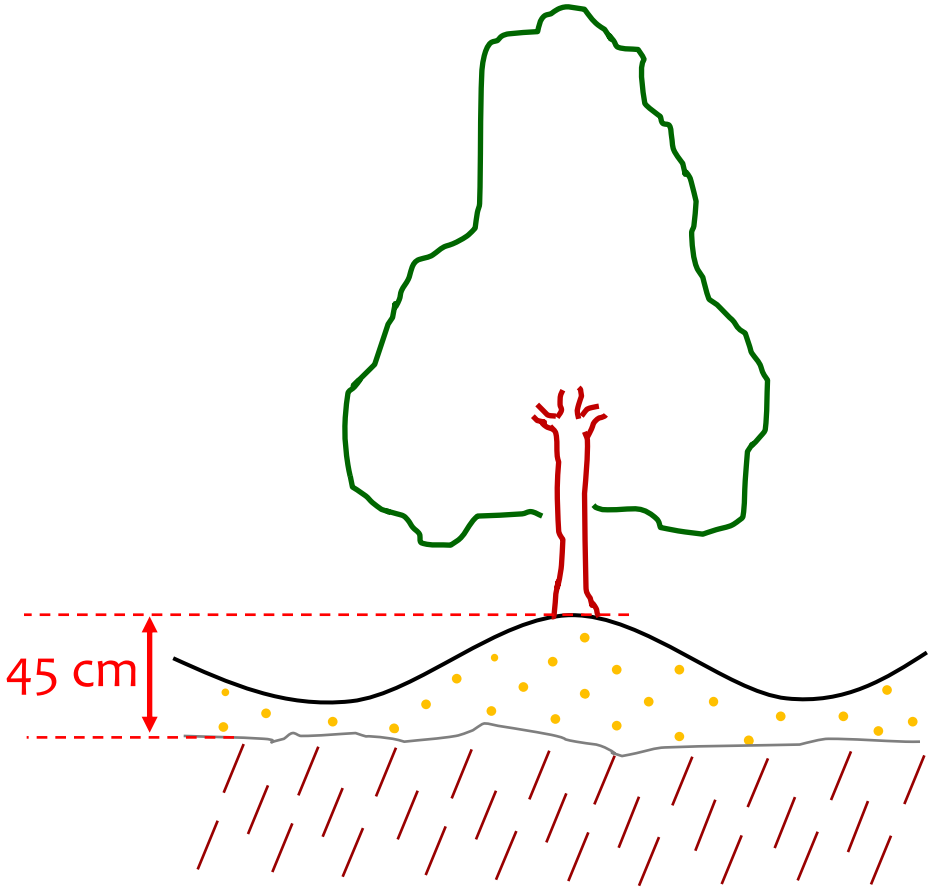
Z (cm)	ϑ_v ($m^3\ m^{-3}$)
10	0.07
20	0.11
30	0.13
40	0.15
60	0.42
100	0.44

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The root zone has a high impact on the management of irrigation: understanding soil water measurements









Z (cm)	ϑ_v ($m^3\ m^{-3}$)
10	0.07
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The root zone has a high impact on the management of irrigation: understanding soil water measurements

Agricultural Water Management 114 (2012) 37–49

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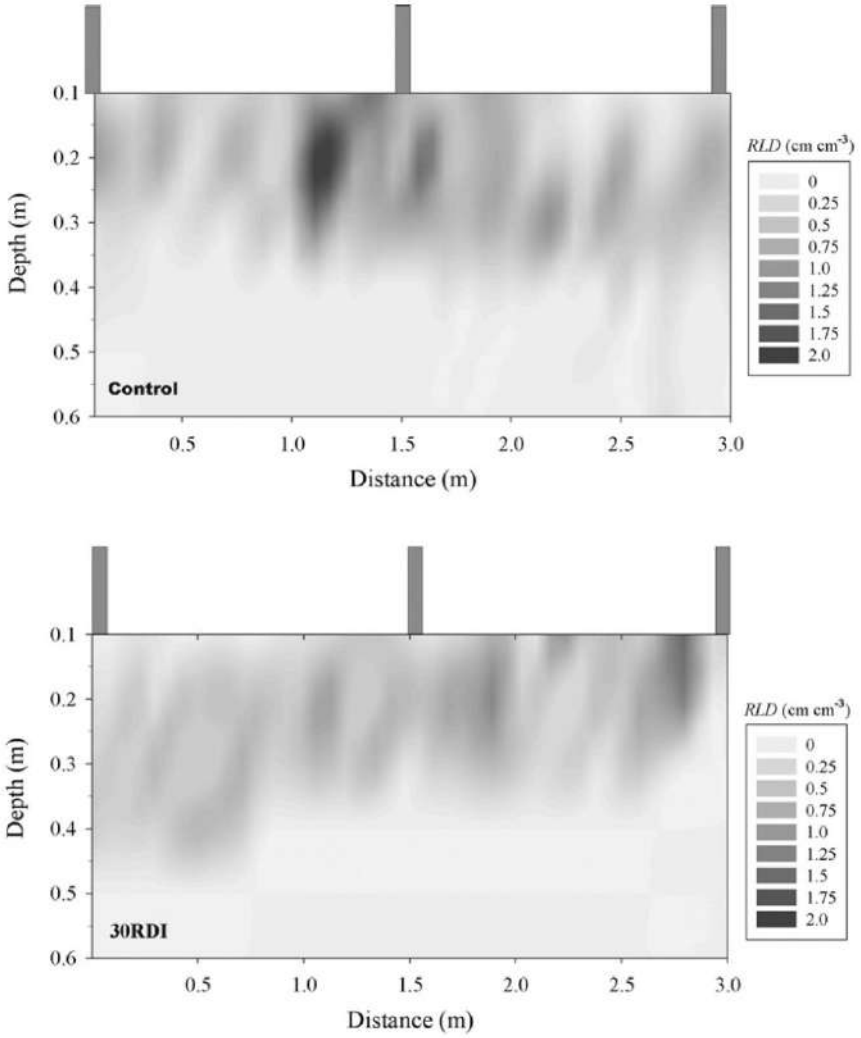
Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Steps toward an improvement in process-based models of water use by fruit trees: A case study in olive

A. Diaz-Espejo[a,e,*], T.N. Buckley[b,e], J.S. Sperry[c,e], M.V. Cuevas[a,e], A. de Cires[d,e], S. Elsayed-Farag[a,e], M.J. Martin-Palomo[f,e], J.L. Muriel[f,e], A. Perez-Martin[a,e], C.M. Rodriguez-Dominguez[a,d,e], A.E. Rubio-Casal[d,e], J.M. Torres-Ruiz[a,e], J.E. Fernández[a,e]

[a] Instituto de Recursos Naturales y Agrobiología, IRNAS-CSIC, Apartado 1052, 41080 Sevilla, Spain
[b] Department of Biology, Sonoma State University, 1801 E Cotati Ave, Rohnert Park, CA 11 94928, USA
[c] Department of Biology, University of Utah, 257S 1400E, Salt Lake City, UT 84112, USA
[d] Departamento de Biología Vegetal y Ecología, Universidad de Sevilla, Sevilla, Spain
[e] ETSIA, Departamento de Ciencias Agroforestales, Universidad de Sevilla, Sevilla, Spain
[f] IFAPA, Centro Las Torres-Tomejil, Junta de Andalucía, Alcala del Río, Sevilla, Spain



Z (cm)	ϑ_v ($m^3\ m^{-3}$)
10	0.07
20	0.11
30	0.13
40	0.15
60	0.42
100	0.44

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The soil hydraulic conductivity (*K*)

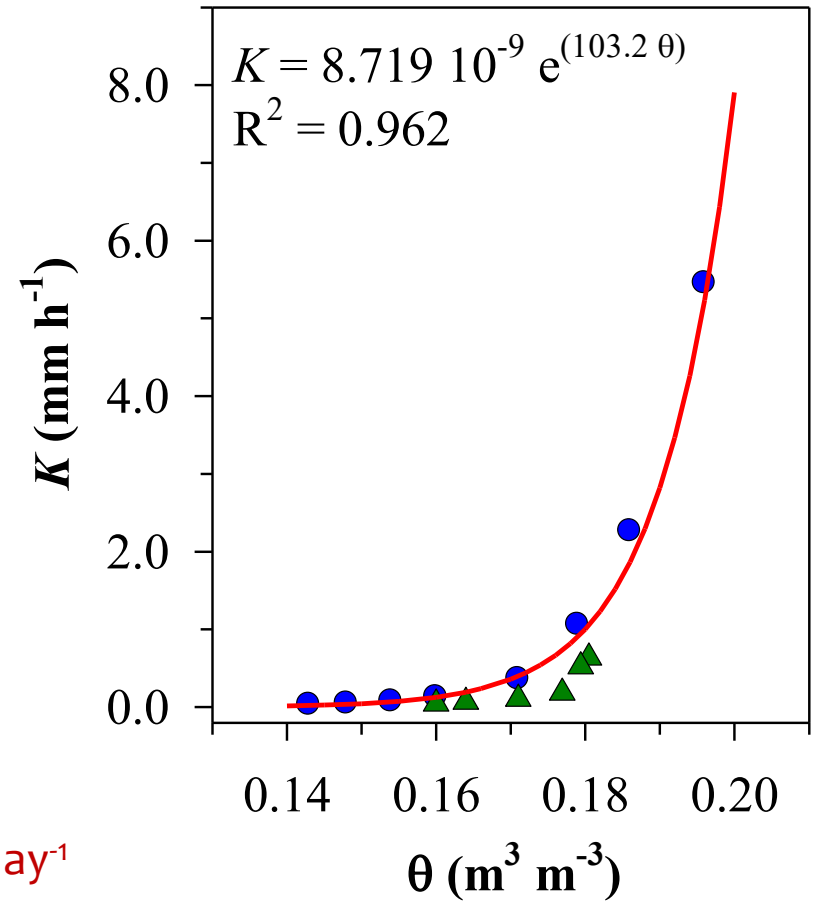
K highly conditions the movement of water in the soil and, therefore, the management of irrigation.

We can use a disk permeameter (or tension infiltrometer) to determine K_{sat}





Scotter, D. R., Clothier, B. E., and Harper, E. R.: Measuring saturated hydraulic conductivity and sorptivity using twin rings, Aust. J. Soil Res., 20, 295–304, 1982.



The most common *K* units are mm h^{-1} and cm day^{-1}

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The soil hydraulic conductivity (*K*)

K highly conditions the movement of water in the soil and, therefore, the management of irrigation.

The disk permeameter can also be used determine *K* under unsaturated conditions.

European Journal of Soil Science

BRITISH SOCIETY OF SOIL SCIENCE

Measuring unsaturated sorptivity and hydraulic conductivity using multiple disc permeameters

K. R. J. SMETTEM, B. E. CLOTHIER

First published: September 1989 | https://doi.org/10.1111/j.1365-2389.1989.tb01297.x | Citations: 127

Soil Science Society of America Journal

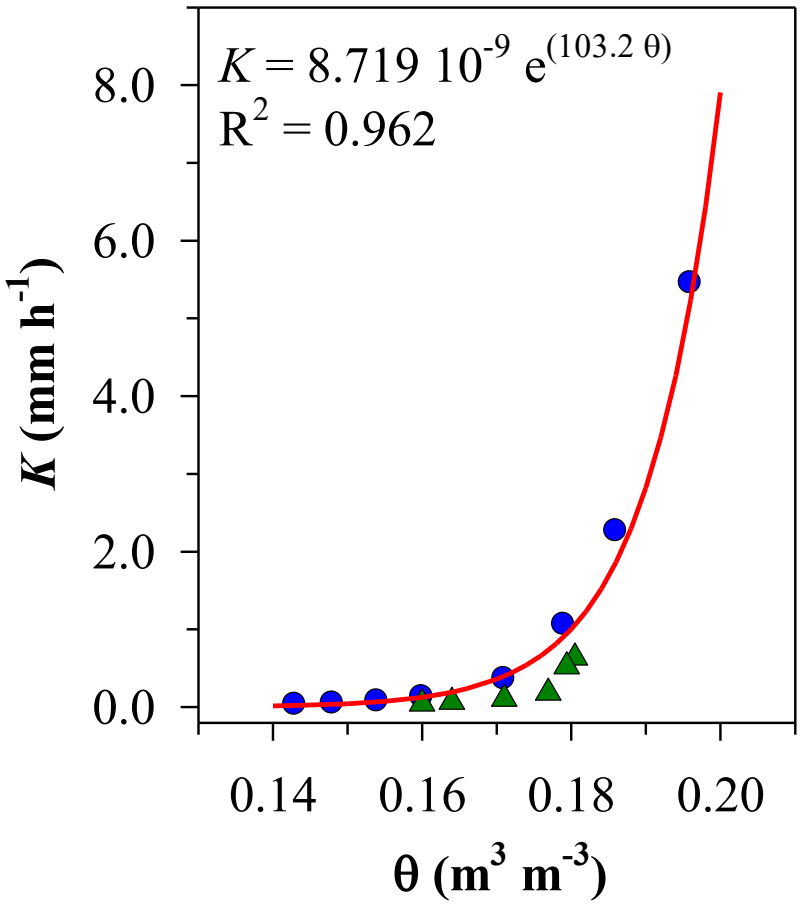
SSSA Soil Science Society of America

Division S-6—Soil & Water Management & Conservation | Full Access

Simple Field Method for Determining Unsaturated Hydraulic Conductivity

Mark D. Ankeny, Mushtaque Ahmed, Thomas C. Kaspar, Robert Horton

First published: 01 March 1991 | https://doi.org/10.2136/sssaj1991.03615995005500020028x | Citations: 351

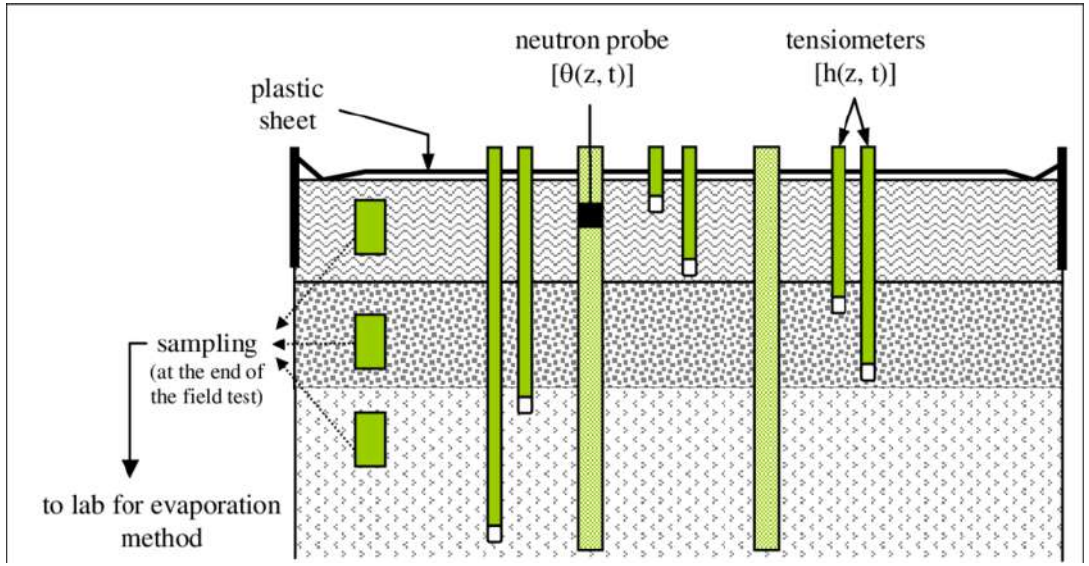


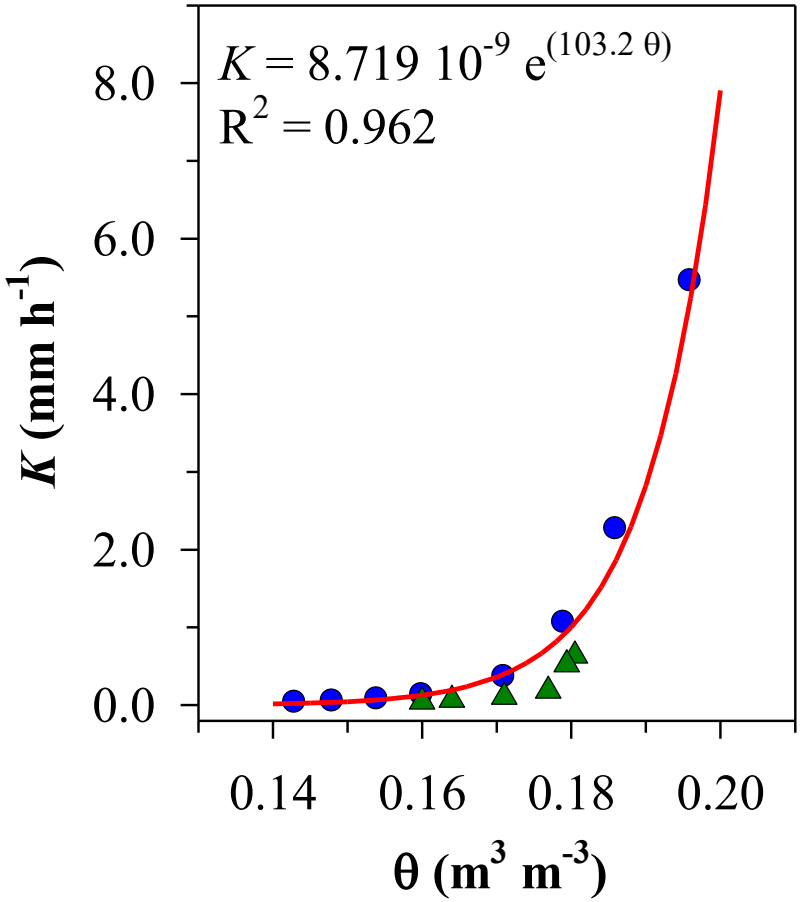
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The soil hydraulic conductivity (*K*)

K highly conditions the movement of water in the soil and, therefore, the management of irrigation.

Values of *K* at non-saturad conditions can be determined with the internal drainage method – limited to *h* < 0.5 bar (Hillel, 1972).





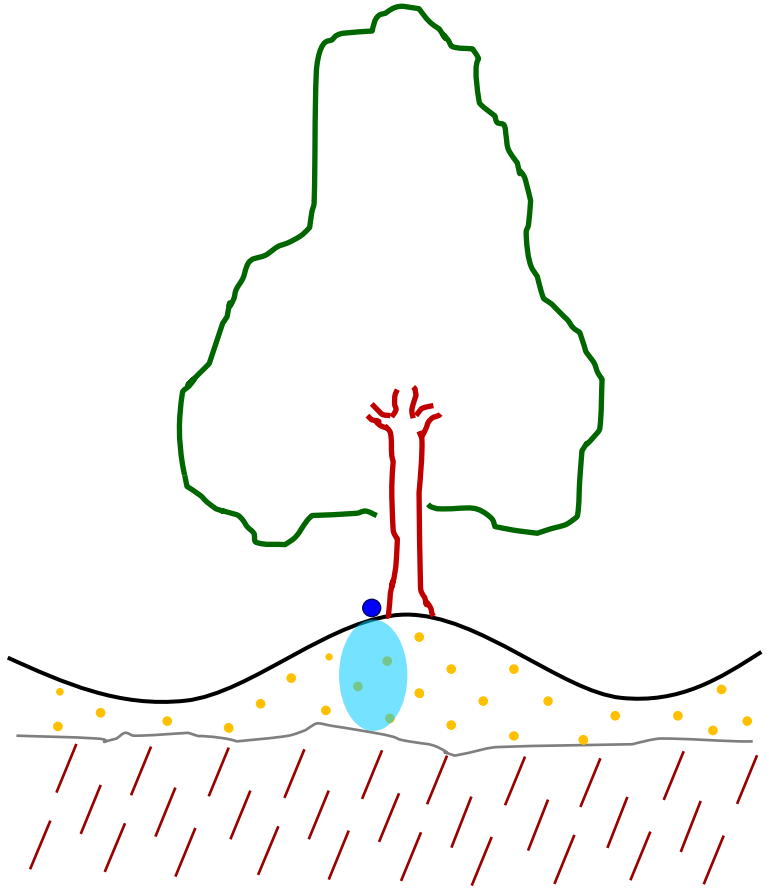
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Percolation conditions the time of irrigation



The *K* value of the top soil layer is high, but very low in the bottom soil layer.

2 h after the beginning of irrigation



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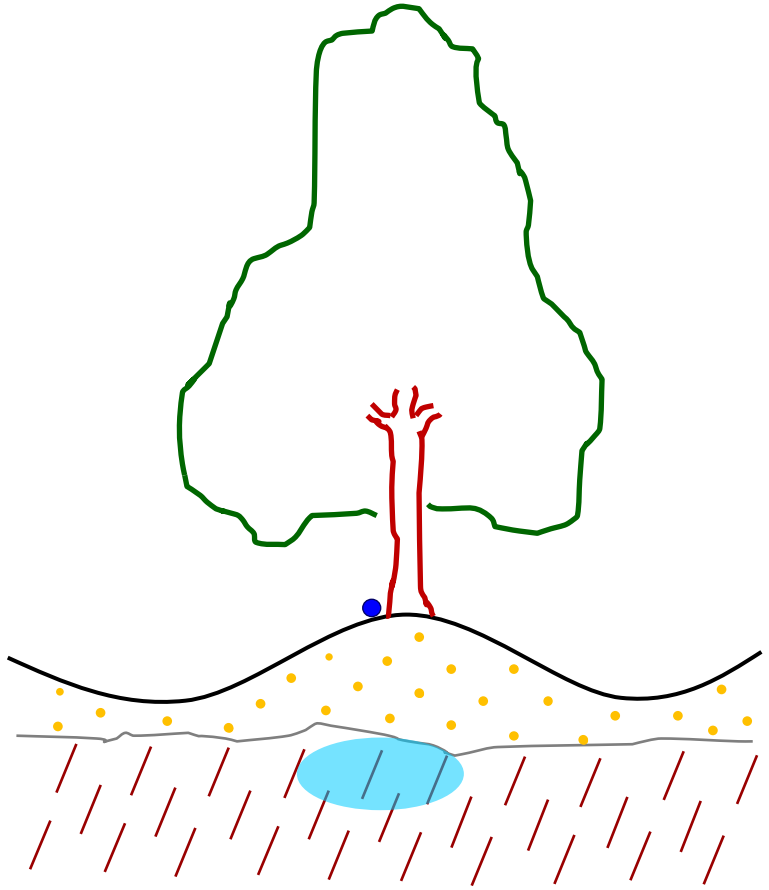
Percolation conditions the time of irrigation



The *K* value of the top soil layer is high,
but very low in the bottom soil layer.

In soil with high *K* values, e.g. sandy soils, we should start irrigation after the opening of stomata.

4 h after the beginning of irrigation



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Irrigating according to the soil texture

Sandy soil: High hydraulic conductivity and low soil water retention capacity

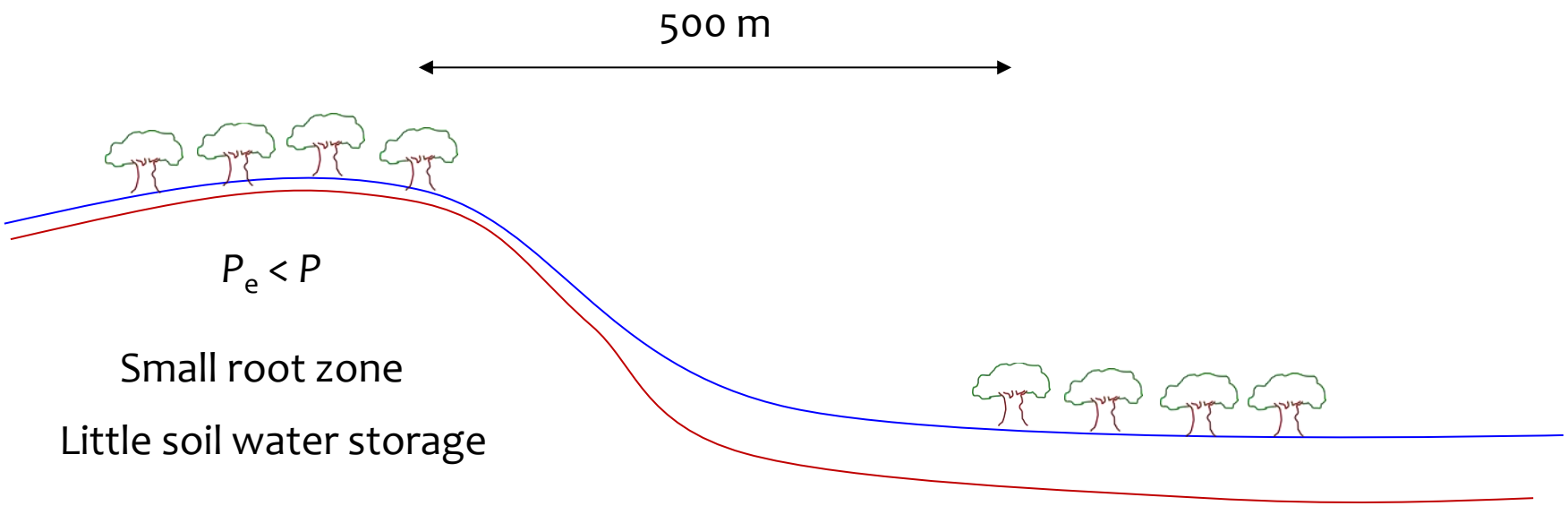
- Emitters with low delivery rate
- High frequency of irrigation (even more than once per day)
- Do not irrigate at night

Clayey soil: Low hydraulic conductivity and high soil water retention capacity

- Emitters with standard delivery rate (not high, to avoid runoff)
- Daily irrigation, except for flooding conditions
- You can irrigate at night if the energy is cheaper

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The terrain is also important



$P_e < P$

Small root zone

Little soil water storage

$P_e \approx P$

Water inputs by runoff

Large root zone

High soil water storage

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Fundamentals of Irrigation

1. Water in the soil

2. The agrometeorological station

3. Plant-based measurements related to water stress

4. Physiological mechanisms related to water stress

5. Agronomic performance

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Atmospheric demand and irrigation

The reference crop evapotranspiration (ET_{ref}) represents the total evaporative water loss, or evapotranspiration, from a standard vegetated surface. When that surface is grass we use the grass reference evapotranspiration (ET_o)

We use ET_o to illustrate the atmospheric demand for the crop water consumption.

Actually, the total evaporative water loss in a crop, or crop evapotranspiration (ET_c) is determined from ET_o:

$$ET_c = K_c\, ET_o$$

$$IN = ET_c - P_e$$

The FAO 56 P-M equation for ET_o:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (6)$$

where

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
$e_s - e_a$ saturation vapour pressure deficit [kPa],
Δ slope vapour pressure curve [kPa $°C^{-1}$],
γ psychrometric constant [kPa $°C^{-1}$].

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The agrometeorological station

Agrometeorological stations are weather stations sited in cropped areas where instruments are exposed to atmospheric conditions similar to those of the surrounding crops.





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The agrometeorological station

But, if you want to use the weather records to estimate ET_o with the FAO P-M equation, the station must accomplish certain standards:

- Sited at the centre of 1 ha of vegetated surface, flat, free of objects. The standard surfaces are grass (12 cm high) or alfalfa (30 cm high), completely shading the ground, well-watered and actively growing.

- Sensors at 2 m above the soil

- Well calibrated sensors!



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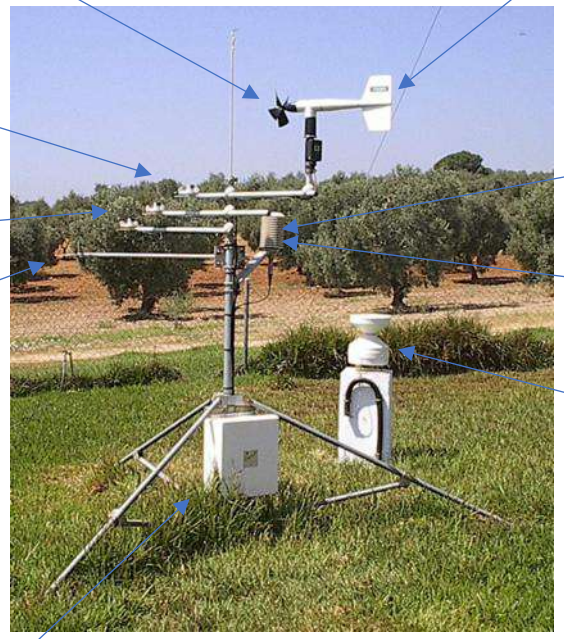
The agrometeorological station





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The agrometeorological station





Evaporation pan

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The agrometeorological station

You may need two weather stations, one to determine ET_o and the other to record the weather conditions surrounding the crop.





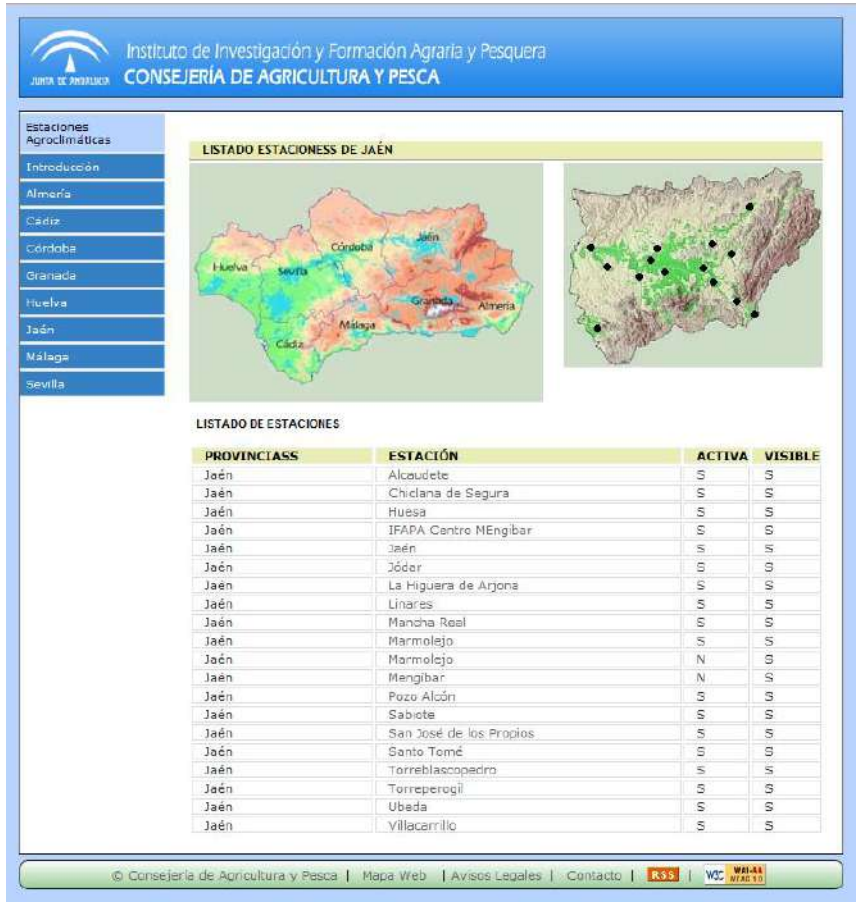
Still, most growers take the ET_o value from a nearby weather station belonging to a public agrometeorological network.

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Agrometeorological station networks

Many central and local governments have a public service of meteorological information.

http://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/







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Fundamentals of Irrigation

1. Water in the soil

2. The agrometeorological station

3. Plant-based measurements related to water stress

4. Physiological mechanisms related to water stress

5. Agronomic performance

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Plant-based variables related to water stress

Leaf or stem water potential
Stomatal conductance









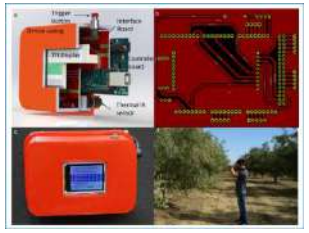
Stem water content
Electric potential

Sap flow
Trunk diameter
Leaf turgor







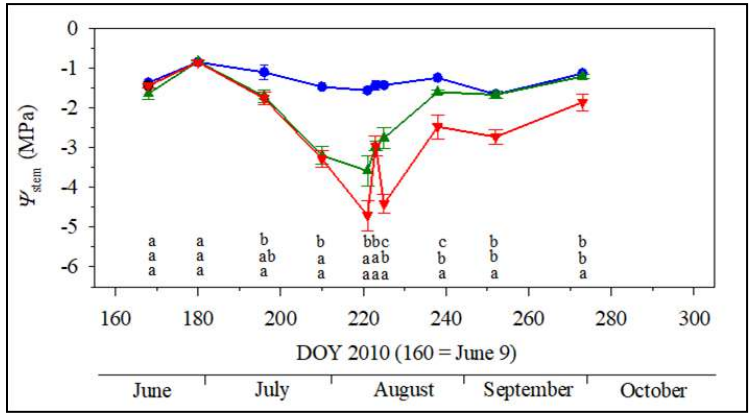
Leaf water content
Canopy temperature

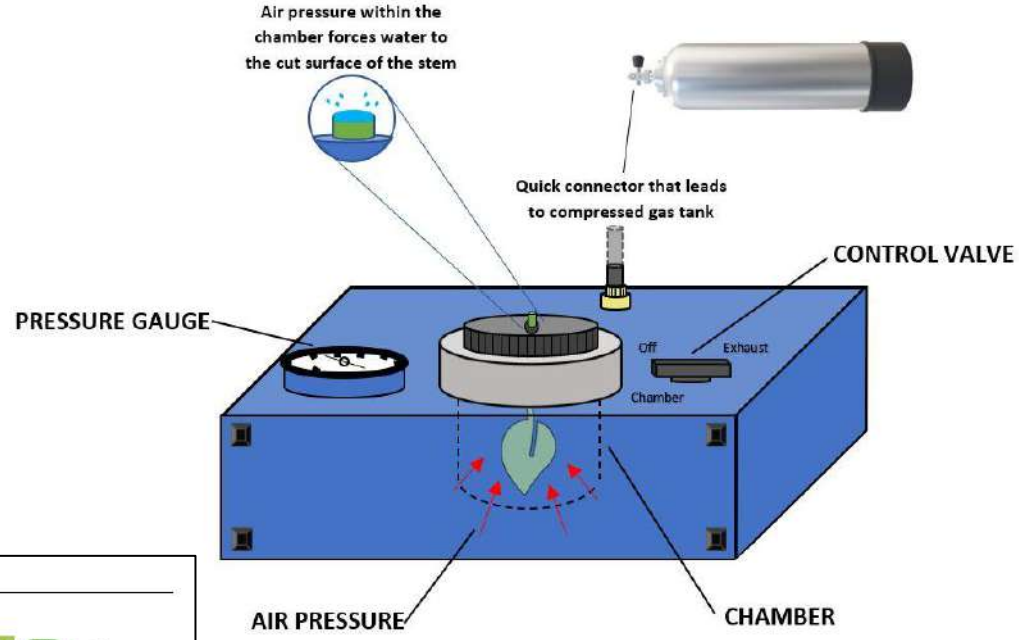
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Leaf/stem water potential



The Scholander-type pressure chamber





Received: 25 January 2022 | Revised: 21 March 2022 | Accepted: 26 March 2022
DOI: 10.1111/pce.14330

ORIGINAL ARTICLE

Plant, Cell & Environment WILEY

Leaf water potential measurements using the pressure chamber: Synthetic testing of assumptions towards best practices for precision and accuracy

Celia M. Rodriguez-Dominguez[1,2] | Alicia Forner[3,4] | Sebastia Martorell[5] | Brendan Choat[6] | Rosana Lopez[7] | Jennifer M. R. Peters[8] | Sebastian Pfautsch[9] | Stefan Mayr[10] | Madeline R. Carins-Murphy[11] | Scott A. M. McAdam[12] | Freya Richardson[11] | Antonio Diaz-Espejo[1,2] | Virginia Hernandez-Santana[1,2] | Paulo E. Menezes-Silva[13] | Jose M. Torres-Ruiz[13] | Timothy A. Batz[12] | Lawren Sack[14]

Automatic measurement of stem water potential

PSY1 Psychrometer

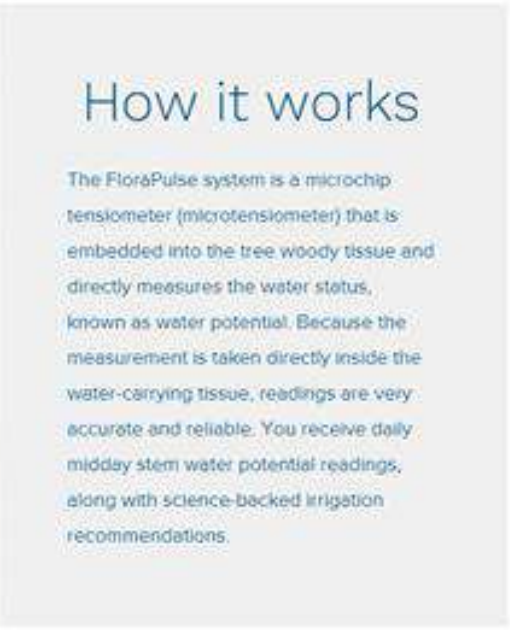
Useful for experiments lasting for a few days. Daily changes in temperature may affect the measurements.



Florapulse microtensiometer

Useful for seasonal measurements (depending on the plant reaction).





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Most widely used plant water potential measurements

Predawn leaf water potential (Ψ_{pd}, MPa). Informs on the level of rehydration achieved during the night. Values of Ψ_{pd} close to zero indicate that the water in the soil is enough for the plant to recover from water stress at night. For olive, Ψ_{pd} values more negative than -0.5 MPa shows a significant level of water stress.

Minimum leaf water potential ($\Psi_{min\text{-}leaf}$, MPa). Informs on the maximum level of water stress occurring in the plant on the sampling day. For olive, $\Psi_{min\text{-}leaf}$ values more negative than -1.2 MPa show the threshold in between low and moderate levels of water stress (Fernández et al., 2013).

Minimum stem water potential ($\Psi_{min\text{-}stem}$, MPa). Informs on the maximum level of water stress occurring in the planton the sampling day. For olive, $\Psi_{min\text{-}stem}$ values more negative than -1.2 MPa to -2.0 MPa, depending on the growing conditions, have been defined as thresholds for water stress in olive (Moriana et al., 2012).

For $\Psi_{min\text{-}stem}$ we use the apical part of a shoot covered with aluminium bag some 0.5-2 h before sampling, or from a shaded site inside the canopy (no covering needed).

K.D. Shackel et al. (1997) Plant water status as an index of irrigation need in deciduous fruit trees. HortTechnology 7(1): 23-29.

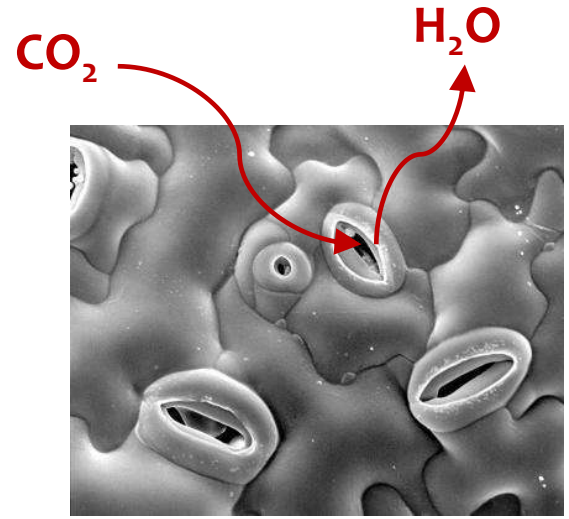
A. Naor (2000) Midday stem water potential as a plant water stress indicator for irrigation scheduling in fruit trees. Acta Hortic. 537: 447-454.

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Gas exchange measurements



Porometer. It measures the leaf conductance, g_l (mol m^{-2} s^{-1}). If the cuticle is waterproof, we talk of stomatal conductance, g_s.
For well watered olive trees, maximum g_s values are ca. 0.25-0.30 mol m^{-2} s^{-1}.





Infrared gas analyser (IRGA), also known as portable photosynthesis system. It measures the CO_2 net assimilation, A_N, or net photosynthesis rate, P_N (µmol m^{-2} s^{-1}).
For olive, maximum A_N values are ca. 18-20 µmol m^{-2} s^{-1}.

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Stomatal conductance can be estimated from sap flow measurements





Agricultural and Forest Meteorology 218–219 (2016) 92–101

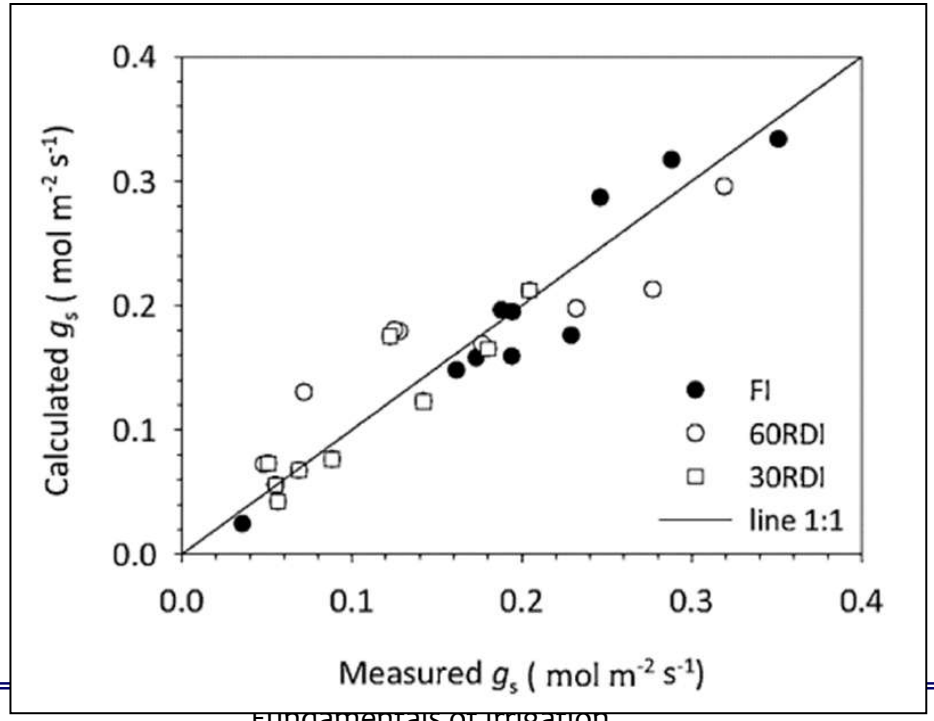
Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit

V. Hernandez-Santana[a], J.E. Fernández[a], C.M. Rodriguez-Dominguez[a,b], R. Romero[a], A. Diaz-Espejo[a,*]

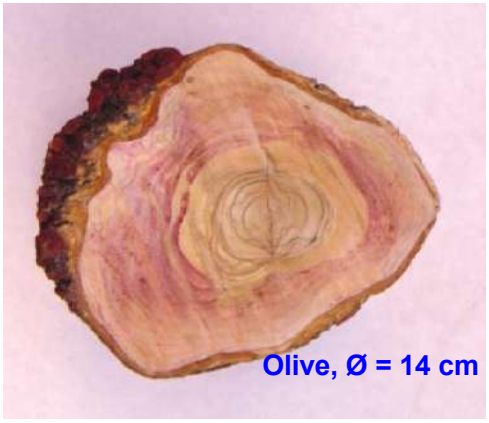


$g_s \approx J_s / D_a$

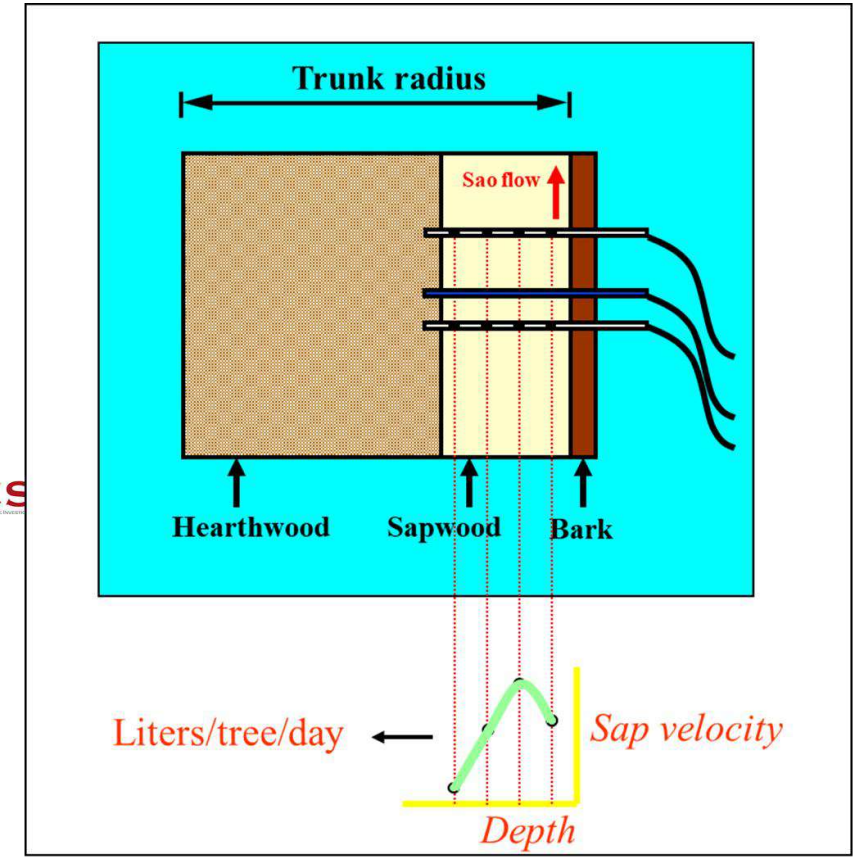
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Sap flow

The compensation heat-pulse method







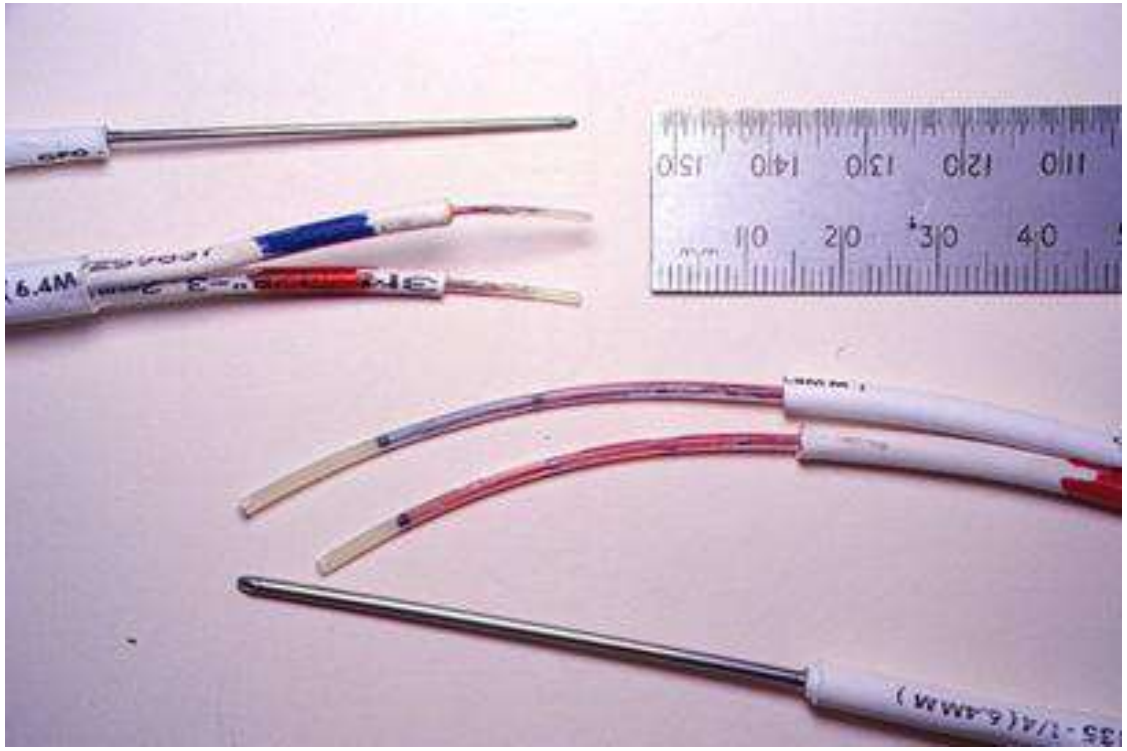


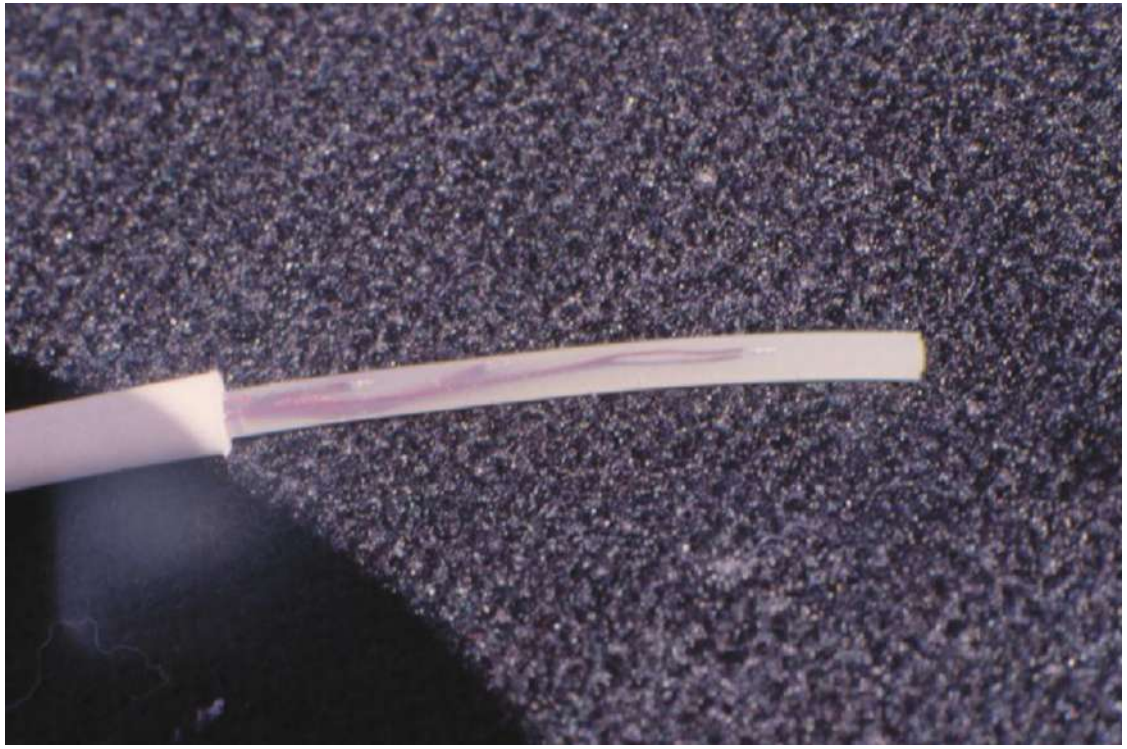




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Sap flow probes





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Sap flow methods

https://www.ishs.org/sap-flow/ishs-working-group-sap-flow-online-resources

Documents:

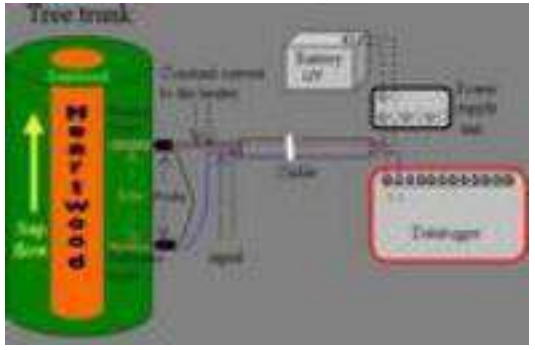
- A summary of the main methods of Sap Flow
- A list of references to key papers on Sap Flow
- Granier's Thermal Dissipation Probe Method for Measuring Sap Flow in trees
- A list with the main manufacturers of Sap Flow equipment









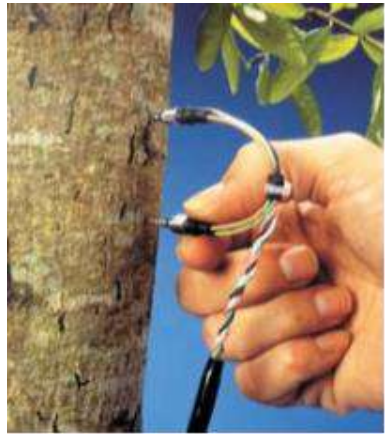






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Invasive vs. non-invasive SF methods





For invasive methods, you have to be use correction coefficients derived from calibration experiments.

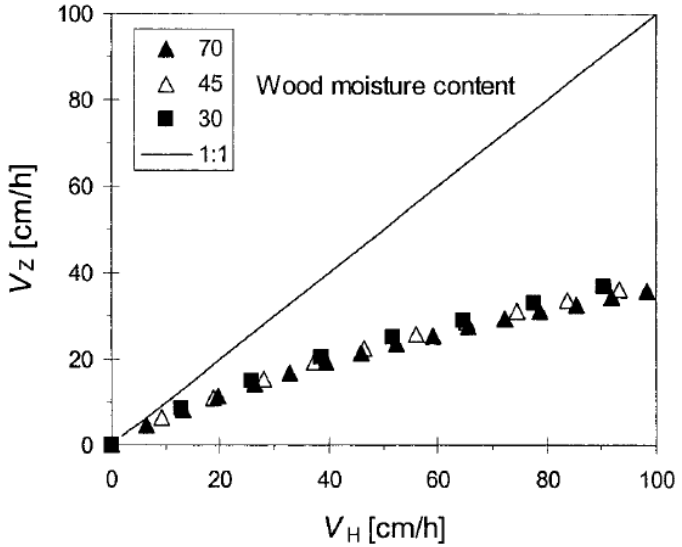


Fig. 2. Influence of wood moisture content ($m^3\ m^{-3}$) on the relationship between measured heat pulse velocity (Vz) and the actual heat pulse velocity (V_H). This relationship was determined using the numerical model. The temperature probes are Teflon, and the heater is stainless steel.

Table 1. Correction factors for the compensation method using 1.6-mm-diam. probes placed at a distance of $x_U = -5$ mm upstream and $x_D = 10$ mm downstream from the heater.

	Coefficients in Eq. [7]		
Wound width	a_0	a_1	a_2
mm			
1.6	−5.48E−01	1.33E+00	4.00E−02
1.8	−4.26E−01	1.31E+00	4.94E−02
2.0	−9.63E−02	1.24E+00	6.34E−02
2.2	1.31E−01	1.19E+00	7.36E−02
2.4	3.94E−01	1.12E+00	8.78E−02
2.6	8.36E−01	9.98E−01	1.07E−01
2.8	1.51E+00	7.91E−01	1.32E−01
3.0	1.79E+00	6.86E−01	1.52E−01
3.2	2.31E+00	5.02E−01	1.78E−01
3.4	2.86E+00	2.71E−01	2.11E−01

The compensation heat pulse method

$$V = a_0 + a_1 V_H + a_2 V_H^2$$

$$J_S = (kF_M + F_L)V \quad \text{sap flux density}$$

$$F = 2\pi \int_H^R r J_S(r) dr \quad \text{volume sap flux}$$

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Calibration of the heat-pulse compensation method

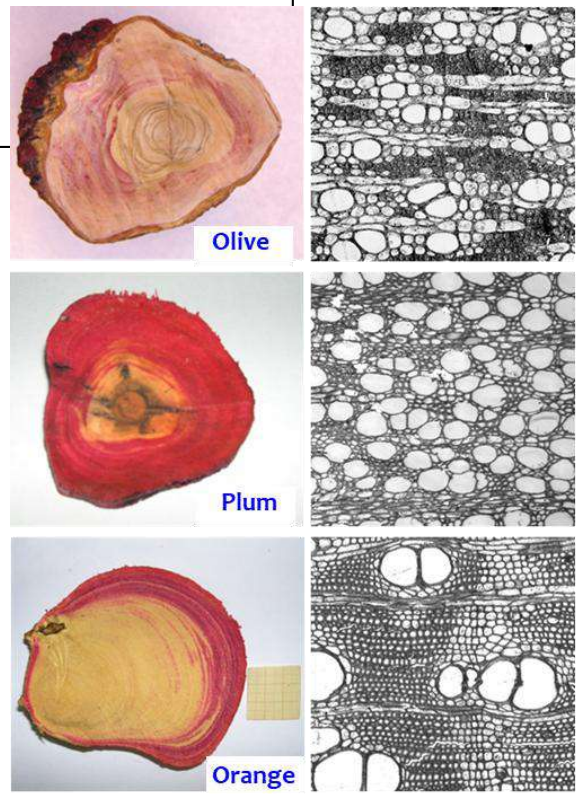
Tree Physiology 26, 719–728
© 2006 Heron Publishing—Victoria, Canada

Calibration of sap flow estimated by the compensation heat pulse method in olive, plum and orange trees: relationships with xylem anatomy

J. E. FERNÁNDEZ,[1,3] P. J. DURÁN,[1] M. J. PALOMO,[2] A. DIAZ-ESPEJO,[1] V. CHAMORRO[1] and I. F. GIRÓN[1]

[1] *Instituto de Recursos Naturales y Agrobiología, Apartado 1052, 41080 Sevilla, Spain*
[2] *E.U.I.T.A., Departamento de Ciencias Agroforestales, Carretera de Utrera km 1, 41013 Sevilla, Spain*
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Received August 2, 2005; accepted September 27, 2005; published online March 1, 2006









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The compensation heat-pulse method

Agronomy Journal (2003) Vol. 95 November-December, 1371-1379

Theory and Practical Application of Heat Pulse to Measure Sap Flow

Steve Green,* Brent Clothier, and Bryan Jardine



ELSEVIER

Agricultural Water Management 51 (2001) 99–123

Agricultural water management

www.elsevier.com/locate/agwat

Heat-pulse measurements of sap flow in olives for automating irrigation: tests, root flow and diagnostics of water stress

J.E. Fernández[a,*], M.J. Palomo[a], A. Díaz-Espejo[a], B.E. Clothier[b], S.R. Green[b], I.F. Girón[a], F. Moreno[a]

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[b]*Environment Group, HortResearch, PB 11-030, Palmerston North 5301, New Zealand*

Accepted 9 April 2001

Trunk Diameter Variations

Holders of Al and INVAR (alloy of Ni and Fe with minimal thermal expansion)



Linear Variable Displacement/Differential Transducers/Transformers (LVDT sensors)

The "Plantsens" dendrometer



Related system



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The Verdtech station

It collects records of TDV, main weather variables and soil water content.







www.Verdtech.es
www.Phytech.com

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Other types of dendrometer











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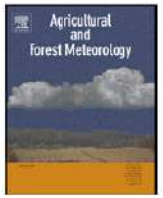
Trunk Diameter Variations

Agricultural and Forest Meteorology 150 (2010) 135–151

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Review

Irrigation scheduling from stem diameter variations: A review

J.E. Fernández *, M.V. Cuevas

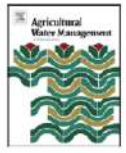
Instituto de Recursos Naturales y Agrobiología (IRNAS-CSIC), Avenida de Reina Mercedes, No. 10, 41012 Seville, Spain

Agricultural Water Management 97 (2010) 1293–1302

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat



Assessment of trunk diameter variation derived indices as water stress indicators in mature olive trees

M.V. Cuevas [a], J.M. Torres-Ruiz [a], R. Álvarez [b], M.D. Jiménez [b], J. Cuerva [b], J.E. Fernández [a,*]

[a] *Instituto de Recursos Naturales y Agrobiología (IRNASE-CSIC), Avenida de Reina Mercedes, n° 10, 41012 Seville, Spain*
[b] *Verdtech Nuevo Campo S.A., Avenida Dehesa del Piorno, 1, Polígono Industrial La Gravera, 21440 Lepe, Spain*

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Leaf turgor

The ZIM probe











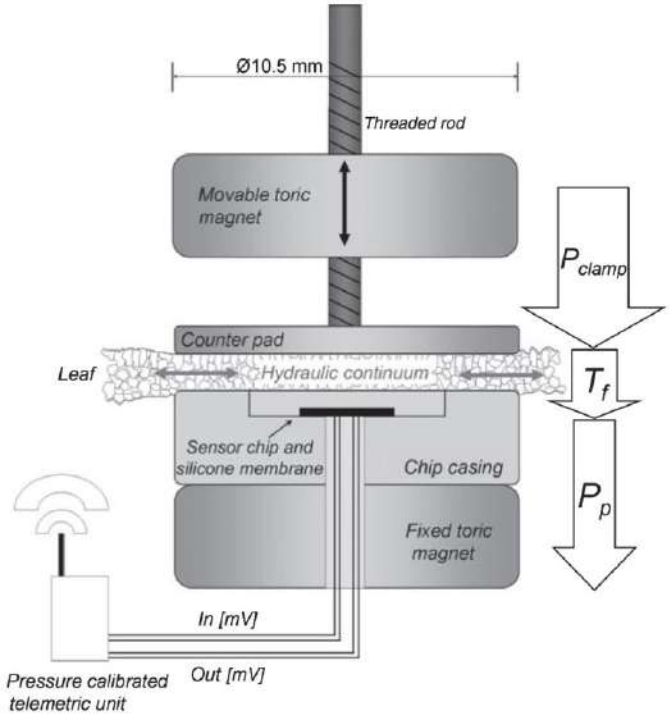


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SI from leaf turgor measurements



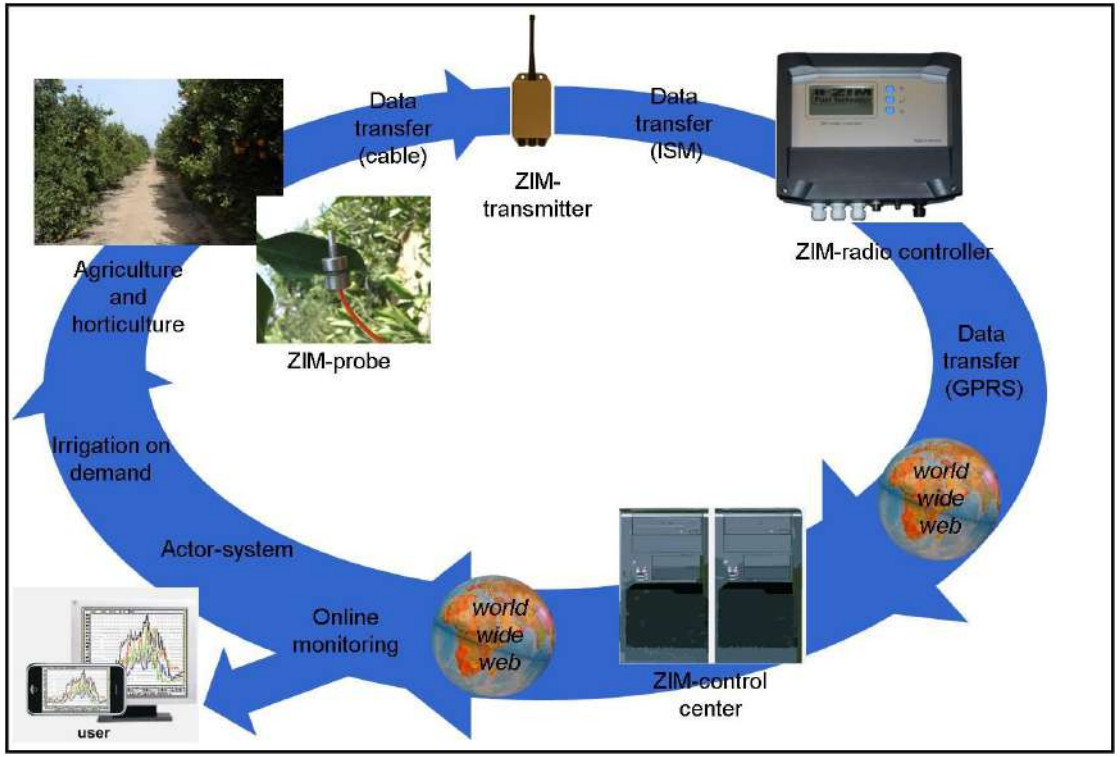
$\Psi_{leaf} = TP - \pi_o$



P_p is inversely correlated with TP

www.zim-plant-technology.com

Yara zim-plant-technology



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Leaf turgor

Journal of Experimental Botany, Vol. 59, No. 11, pp. 3157–3167, 2008
doi:10.1093/jxb/ern171
This paper is available online free of all access charges (see http://jxb.oxfordjournals.org/open_access.html for further details)
Journal of Experimental Botany
www.jxb.oxfordjournals.org

RESEARCH PAPER

A novel, non-invasive, online-monitoring, versatile and easy plant-based probe for measuring leaf water status

D. Zimmermann[1,*,†], R. Reuss[2,†], M. Westhoff[2,†], P. Geßner[2], W. Bauer[2], E. Bamberg[1], F-W. Bentrup[3] and U. Zimmermann[2]

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Agricultural Water Management 100 (2011) 25–35

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Online-monitoring of tree water stress in a hedgerow olive orchard using the leaf patch clamp pressure probe

J.E. Fernández[a,*], C.M. Rodriguez-Dominguez[a], A. Perez-Martin[a], U. Zimmermann[b], S. Rüger[b], M.J. Martín-Palomo[c], J.M. Torres-Ruiz[a], M.V. Cuevas[a], C. Sann[b,d], W. Ehrenberger[b,d], A. Diaz-Espejo[a]

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plant biology

Plant Biology ISSN 1435-8603

RESEARCH PAPER

Leaf patch clamp pressure probe measurements on olive leaves in a nearly turgorless state

W. Ehrenberger[1,2], S. Rüger[2], C. M. Rodríguez-Domínguez[3], A. Díaz-Espejo[3], J.E. Fernández[3], J. Moreno[4], D. Zimmermann[1], V. L. Sukhorukov[1] & U. Zimmermann[2]

1 Lehrstuhl für Biotechnologie, Biozentrum, Universität Würzburg, Würzburg, Germany
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doi:10.1111/j.1438-8677.2011.00545.x

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Leaf water content

NIR spectroscopy can be used to measure the dynamics of leaf water content.

frontiers in Plant Science

ORIGINAL RESEARCH
published: 30 January 2018
doi: 10.3389/fpls.2018.00059

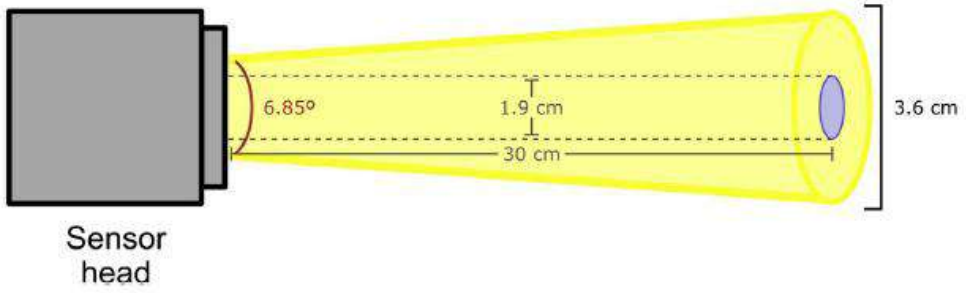
Development and Validation of a New Methodology to Assess the Vineyard Water Status by On-the-Go Near Infrared Spectroscopy

*Maria P. Diago, Juan Fernández-Novales, Salvador Gutiérrez, Miguel Marañón and Javier Tardaguila**

Instituto de Ciencias de la Vid y del Vino - CSIC, University of La Rioja and Gobierno de La Rioja, Logroño, Spain



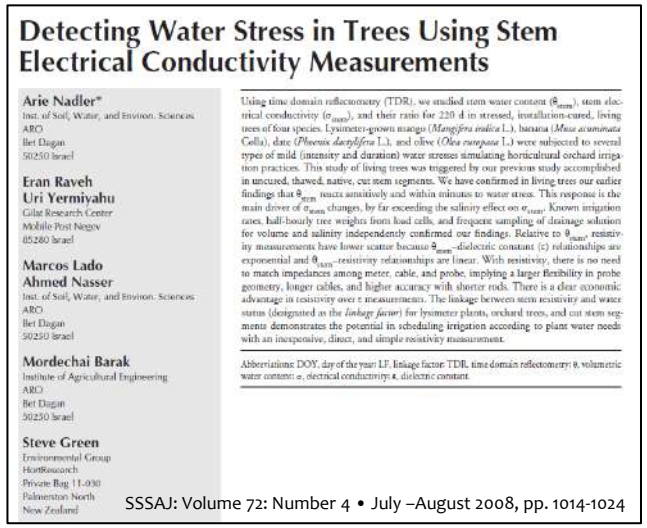




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Stem water content

TDR sensors can be used to measure water content and electrical conductivity in the stem.



Detecting Water Stress in Trees Using Stem Electrical Conductivity Measurements

Arie Nadler*
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Eran Raveh
Uri Yermiyahu
Gilat Research Center
Mobile Post Negev
85280 Israel

Marcos Lado
Ahmed Nasser
Inst. of Soil, Water, and Environ. Sciences
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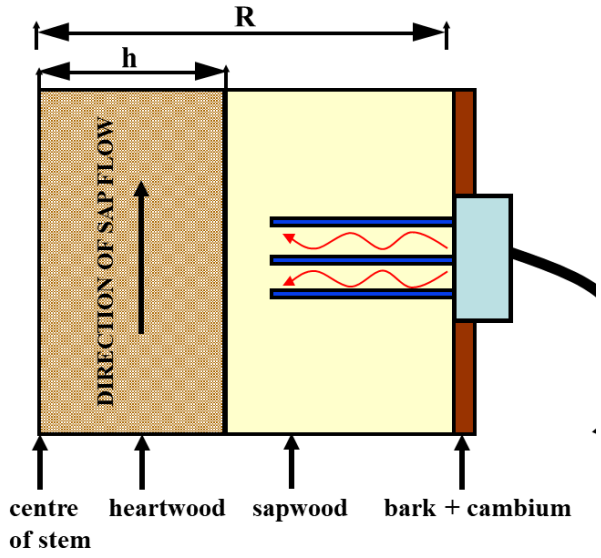
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Palmerston North
New Zealand

Using time domain reflectometry (TDR), we studied stem water content (θ_{stem}), stem electrical conductivity (σ_{stem}), and their ratio for 220 d in stressed, installation-cured, living trees of four species. Lysimeter-grown mango (*Mangifera indica* L.), banana (*Musa acuminata* Colla), date (*Phoenix dactylifera* L.), and olive (*Olea europaea* L.) were subjected to several types of mild (intensity and duration) water stresses simulating horticultural orchard irrigation practices. This study of living trees was triggered by our previous study accomplished in uncured, thawed, native, cut stem segments. We have confirmed in living trees our earlier findings that θ_{stem} reacts sensitively and within minutes to water stress. This response is the main driver of σ_{stem} changes, by far exceeding the salinity effect on σ_{stem}. Known irrigation rates, half-hourly tree weights from load cells, and frequent sampling of drainage solution for volume and salinity independently confirmed our findings. Relative to θ_{stem}, resistivity measurements have lower scatter because θ_{stem}–dielectric constant (ε) relationships are exponential and θ_{stem}–resistivity relationships are linear. With resistivity, there is no need to match impedances among meter, cable, and probe, implying a larger flexibility in probe geometry, longer cables, and higher accuracy with shorter rods. There is a clear economic advantage in resistivity over ε measurements. The linkage between stem resistivity and water status (designated as the *linkage factor*) for lysimeter plants, orchard trees, and cut stem segments demonstrates the potential in scheduling irrigation according to plant water needs with an inexpensive, direct, and simple resistivity measurement.

Abbreviations: DOY, day of the year; LF, linkage factor; TDR, time domain reflectometry; θ, volumetric water content; σ, electrical conductivity; ε, dielectric constant.

SSSAJ: Volume 72: Number 4 • July –August 2008, pp. 1014-1024







SOIL SCI. SOC. AM. J., VOL. 70, MARCH–APRIL 2006

Stress Induced Water Content Variations in Mango Stem by Time Domain Reflectometry

A. Nadler,* Eran Raveh, Uri Yermiyahu, and S. Green

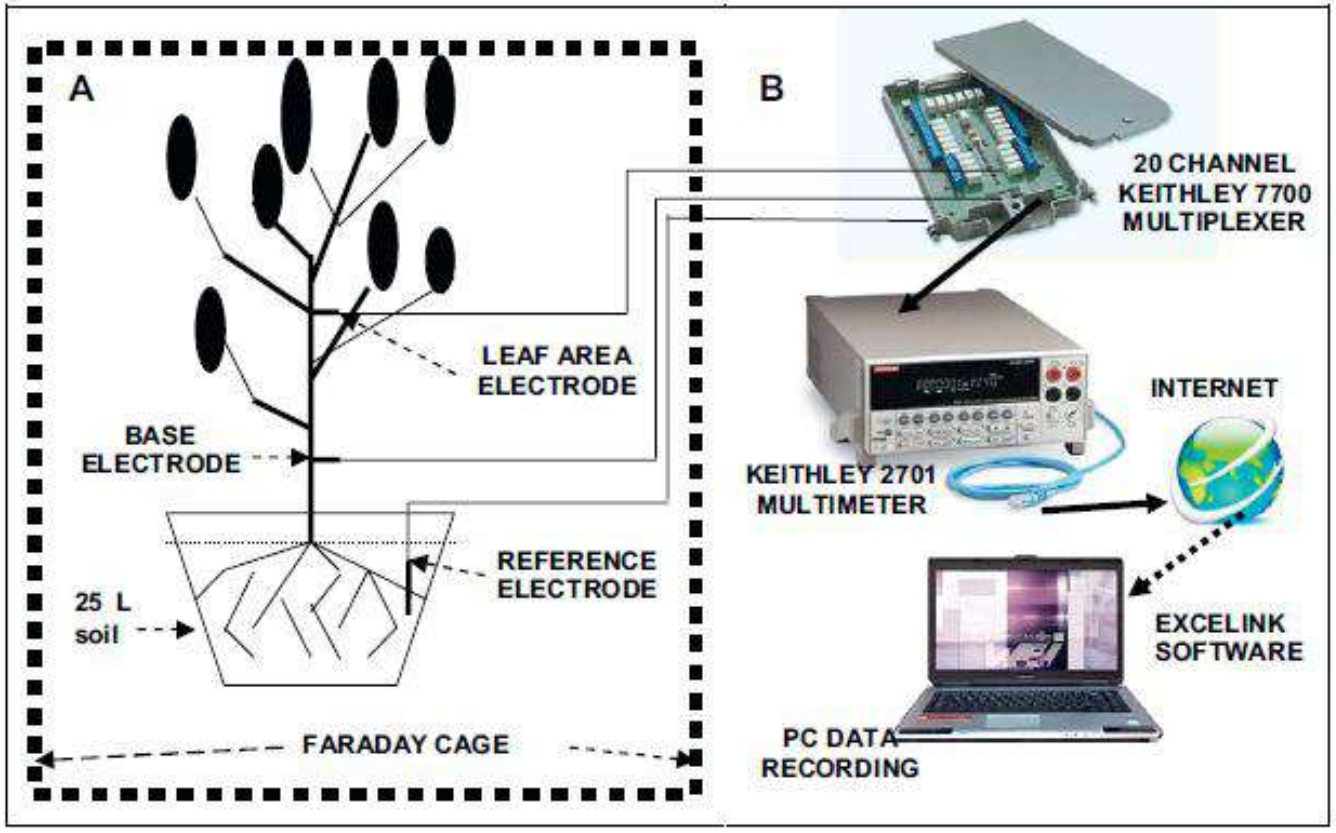
So far, they are being used at the research level only:

- Influence of temperature on the outputs
- Expensive
- Heavy data processing required



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Electric potential





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Electric potential

Journal of Plant Physiology 168 (2011) 103–108

Contents lists available at ScienceDirect

Journal of Plant Physiology

journal homepage: www.elsevier.de/jplph

Evidence for the transmission of information through electric potentials in injured avocado trees

Patricio Oyarce, Luis Gurovich*

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ARTICLE INFO

Article history:
Received 8 January 2010
Received in revised form 15 June 2010
Accepted 16 June 2010

Keywords:
Action potential
Mechanical injury
Plant sensors
Plant signaling
Pruning
Variation potential

ABSTRACT

Electrical excitability and signaling, frequently associated with rapid responses to environmental stimuli, have been documented in both animals and higher plants. The presence of electrical potentials (EPs), such as action potentials (APs) and variation potentials (VPs), in plant cells suggests that plants make use of ion channels to transmit information over long distances. The reason why plants have developed pathways for electrical signal transmission is most probably the necessity to respond rapidly, for example, to environmental stress factors.

We examined the nature and specific characteristics of the electrical response to wounding in the woody plant *Persea americana* (avocado). Under field conditions, wounds can be the result of insect activity, strong winds or handling injury during fruit harvest. Evidence for extracellular EP signaling in avocado trees after mechanical injury was expressed in the form of variation potentials. For tipping and pruning, signal velocities of 8.7 and 20.9 cm/s, respectively, were calculated, based on data measured with Ag/AgCl microelectrodes inserted at different positions of the trunk. EP signal intensity decreased with increasing distance between the tipping and pruning point and the electrode. Recovery time to pre-tipping or pre-pruning EP values was also affected by the distance and signal intensity from the tipping or pruning point to the specific electrode position. Real time detection of remote EP signalling can provide an efficient tool for the early detection of insect attacks, strong wind damage or handling injury during fruit harvest.

Our results indicate that electrical signaling in avocado, resulting from microenvironment modifications, can be quantitatively related to the intensity and duration of the stimuli, as well as to the distance between the stimuli site and the location of EP detection. These results may be indicative of the existence of a specific kind of proto-nervous system in plants.

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Introduction

Plant neurobiology is a newly developed discipline in the field of plant physiology, aimed at establishing the structure of information networks that exist within the plant, which are manifested as responses to environmental stimuli by means of electrochemical signals (Baluška et al., 2004; Brenner et al., 2006; Trewavas, 2005). These signals seem to complement other plant signals: hydraulic, mechanical and hormonal, already well documented in plant science (Fromm and Lautner, 2007; Gil et al., 2009). Conducted electrical events may serve for translation of environmental parameters and cues, obtained via sensory systems, into biological information and processes. In plants, most cells are electrically excitable and active, releasing and propagating action potentials (APs), which may affect such central physiological processes as photosynthesis and respiration (Masi et al., 2009). In the last decade, numerous papers have been published on the study of variation and action potentials in plants. However, only rarely have the researches focused on woody plants, although it is in such plants that the need for rapid and efficient signals other than chemicals (hormones) and hydraulic becomes more obvious (Fromm and Lautner, 2007; Gil et al., 2008; Gurovich and Hermosilla, 2009). These studies have associated the effect of water stress, irrigation, and light cycles with electrical signaling in fruit tree species including avocado, blueberry, lemon and olive. Changes in the electrical potential (EP) were detected between the base of the stem and leaf in response to drought, irrigation, and diurnal changes in light and dark. In avocado, the changes in EP between the base of the stem and leaf petiole observed in response to decreased soil water content have been associated with a decrease in stomatal conductance, indicating that stomatal closure might be associated with an electrical signal.

Abbreviations: $\hat{x}$ (cm), distance from injury site to electrode position in the tree; $\hat{y}$ ex, signal relative intensity; t (s), time of electric signal detection by each electrode; r, recovery time of pre-injury signal intensity.

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doi:10.1016/j.jplph.2010.06.003

Journal of Plant Physiology 166 (2009) 290–300

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Electric signalling in fruit trees in response to water applications and light–darkness conditions

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Received 28 January 2008; received in revised form 11 June 2008; accepted 20 June 2008

KEYWORDS
Electric potential;
Light intensity;
Soil water availability;
Tree signalling

Summary

A fundamental property of all living organisms is the generation and conduction of electrochemical impulses throughout their different tissues and organs, resulting from abiotic and biotic changes in environmental conditions. In plants and animals, signal transmission can occur over long and short distances, and it can correspond to intra- and inter-cellular communication mechanisms that determine the physiological behaviour of the organism. Rapid plant and animal responses to environmental changes are associated with electrical excitability and signalling. The same molecules and pathways are used to drive physiological responses, which are characterized by movement (physical displacement) in animals and by continuous growth in plants. In the field of environmental plant electrophysiology, automatic and continuous measurements of electrical potential differences (ΔEP) between plant tissues can be effectively used to study information transport mechanisms and physiological responses that result from external stimuli on plants. A critical mass of data on electrical behaviour in higher plants has accumulated in the last 5 years, establishing plant neurobiology as the most recent discipline of plant science. In this work, electrical potential differences were monitored continuously using Ag/AgCl microelectrodes, which were inserted 15 mm deep into sapwood at various positions in the trunks of several fruit-bearing trees. Electrodes were referenced to an unpolarisable Ag/AgCl microelectrode, which was installed 5 cm deep in the soil. Systematic patterns of ΔEP during day–night cycles and at different conditions of soil water availability are discussed as alternative tools to assess early plant stress

Abbreviations: AP, action potential; EP, electric potential; $\Delta V_{1...n}$, electrical potential differences between the leaf zone and the base of the trunk.

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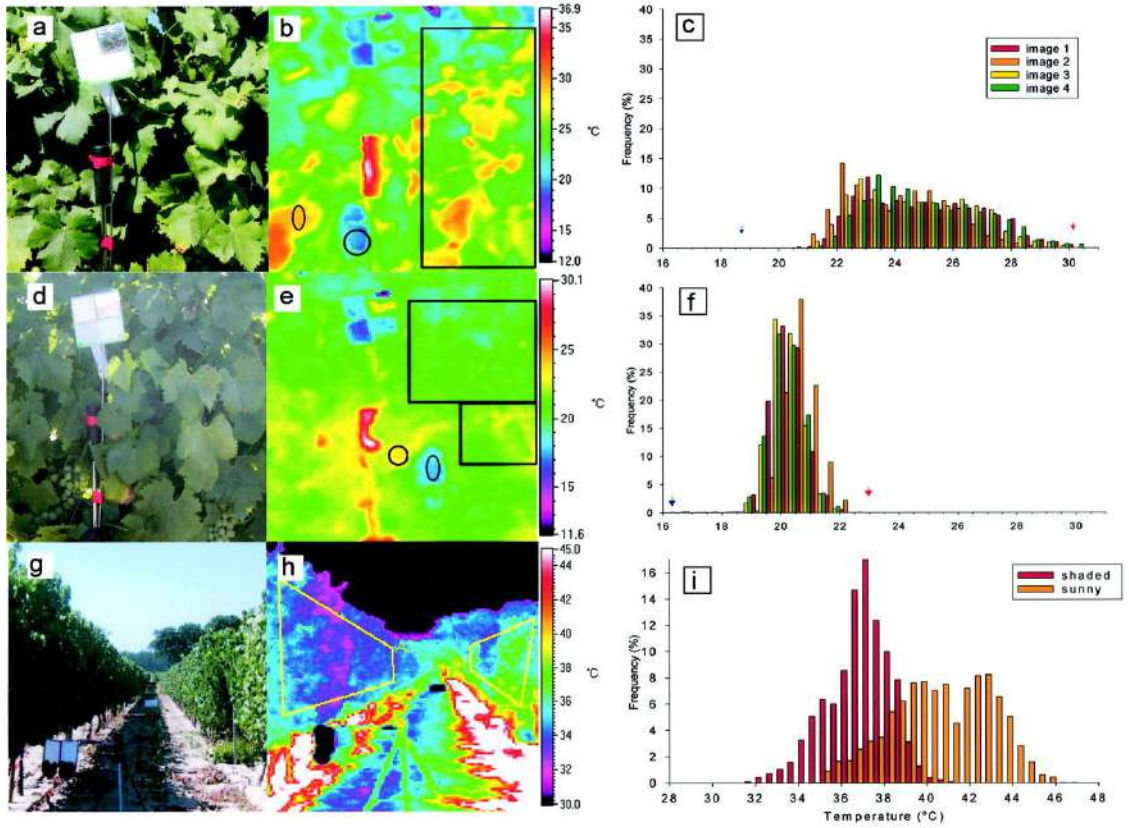
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doi:10.1016/j.jplph.2008.06.004



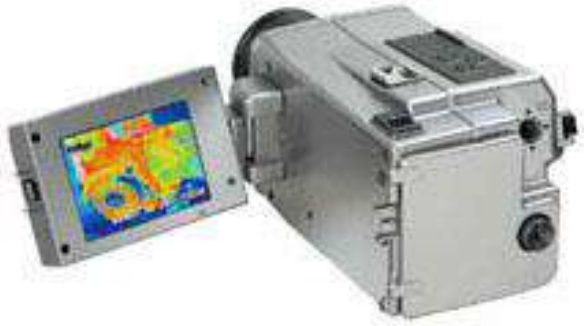
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Canopy temperature

Measurements at the plant level









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Canopy temperature

Measurements at the plant level

remote sensing

MDPI

Article

A New Low-Cost Device Based on Thermal Infrared Sensors for Olive Tree Canopy Temperature Measurement and Water Status Monitoring

Miguel Noguera [1], Borja Millán [1,*], Juan José Pérez-Paredes [2], Juan Manuel Ponce [1], Arturo Aquino [1] and José Manuel Andújar [1]

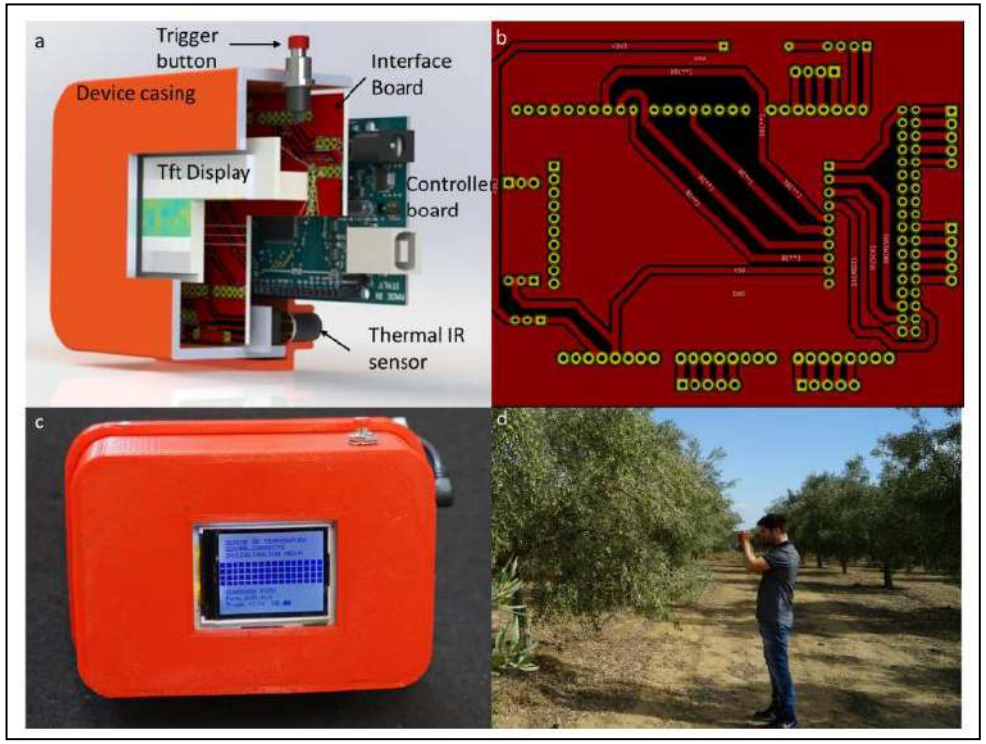
1 University of Huelva, Department of Electronic Engineering, Computer Systems and Automation, La Rábida, Palos de la Frontera, 21819 Huelva, Spain; miguel.noguera@diesia.uhu.es (M.N.); jmponce.real@diesia.uhu.es (J.M.P.); arturo.aquino@diesia.uhu.es (A.A.); andujar@diesia.uhu.es (J.M.A.)

2 Chapingo Autonomous University, Post-graduate program in Agricultural Engineering and Integral Water Use, Chapingo, 56227, Mexico; al18129294@chapingo.mx

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Received: 16 December 2019; Accepted: 21 February 2020; Published: 22 February 2020

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Fundamentals of Irrigation

1. Water in the soil

2. The agrometeorological station

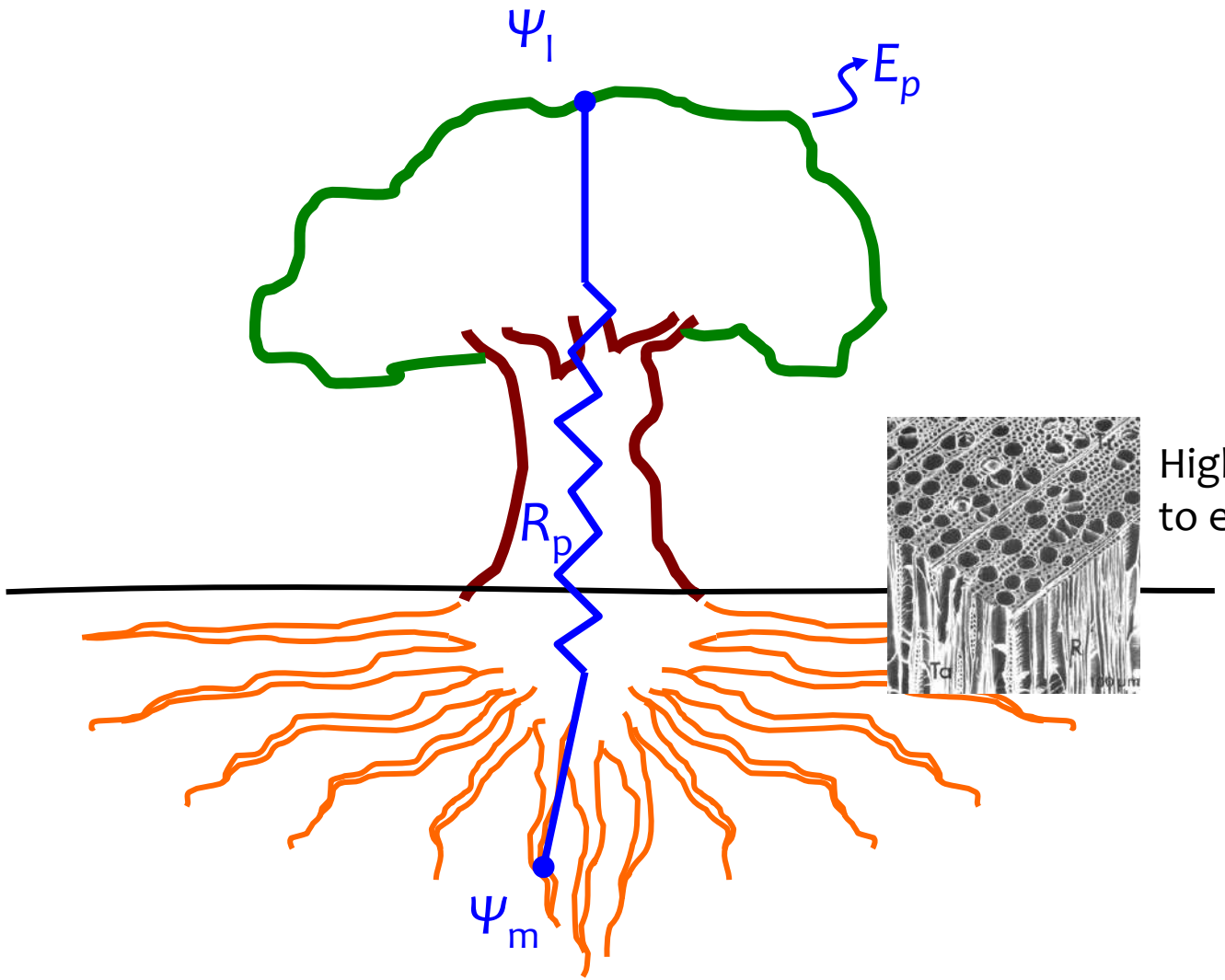
3. Plant-based measurements related to water stress

4. Physiological mechanisms related to water stress

5. Agronomic performance

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Osmotic adjustment in the olive tree



High resistance to embolism

$$E_p = (\Psi_m - \Psi_l) / R_p$$

$$\downarrow$$

$$\Psi_l = \Psi_P - \Psi_\pi \qquad \Psi_{leaf} = TP - \pi_o$$

Ψ_π can decrease 1.5 MPa along the day

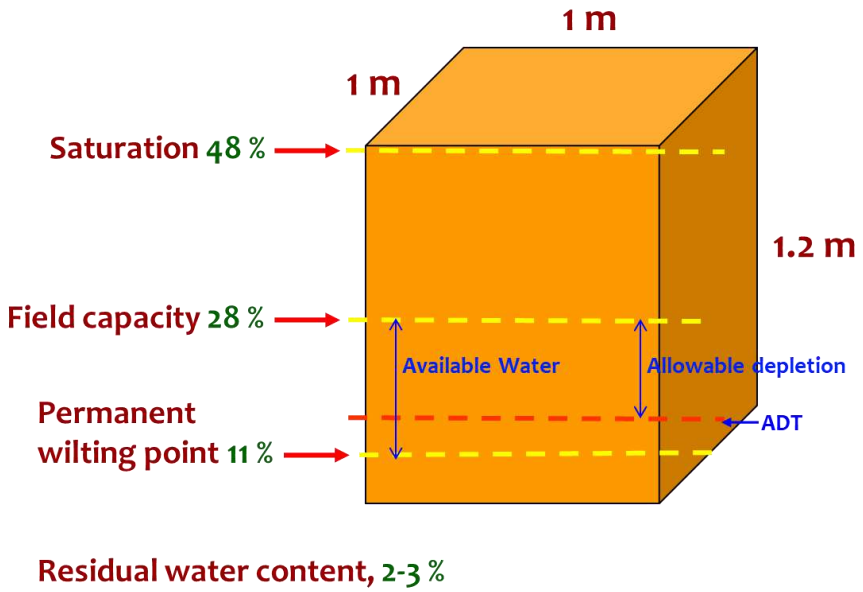
The olive tree has a high capacity to take up water from drying soils

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Water uptake by the olive tree

Moriana et al. (2003) reported $g_{s\text{-}max}$ values of about 0.03 molm^{-2} s^{-1} in mature 'Picual' olive trees growing in soils with $\vartheta_v \approx 0.05$ m^3 m^{-3}, despite $\Psi_{md} \approx -8.0$ MPa.

Perez-Martin et al. (2009) reported $g_{s\text{-}max}$ values of about 0.04 mol m^{-2} s^{-1} in 'Manzanilla' olive trees in soils with $\vartheta_v = 0.06$ m^3 m^{-3}, despite $\Psi_{md} = -5.42$ MPa.



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These results, and those reported by Cuevas et al. (2010), suggest wilting point at Ψ_m values lower than –1.5 MPa.

Moriana, A., Orgaz, F., Pastor, M., Fereres, E., 2003. Yield responses of a mature olive orchard to water deficits. J. Am. Soc. Hortic. Sci. 128 (3), 425–431.

Perez-Martin, A., Flexas, J., Ribas-Carbó, M., Bota, J., Tomás, M., Infante, J.M., Diaz-Espejo, A., 2009. Interactive effects of soil water deficit and air vapour pressure deficit on mesophyll conductance to CO2 in Vitis vinifera and Olea europea. J. Exp. Bot. 60 (8), 2391–2405.

Cuevas MV, Torres-Ruiz JM, Álvarez R, Jiménez MD, Cuerva J, Fernández JE (2010) Assessment of trunk diameter variation derived indices as water stress indicators in mature olive trees. Agric. Water Manag. 97:1293–1302

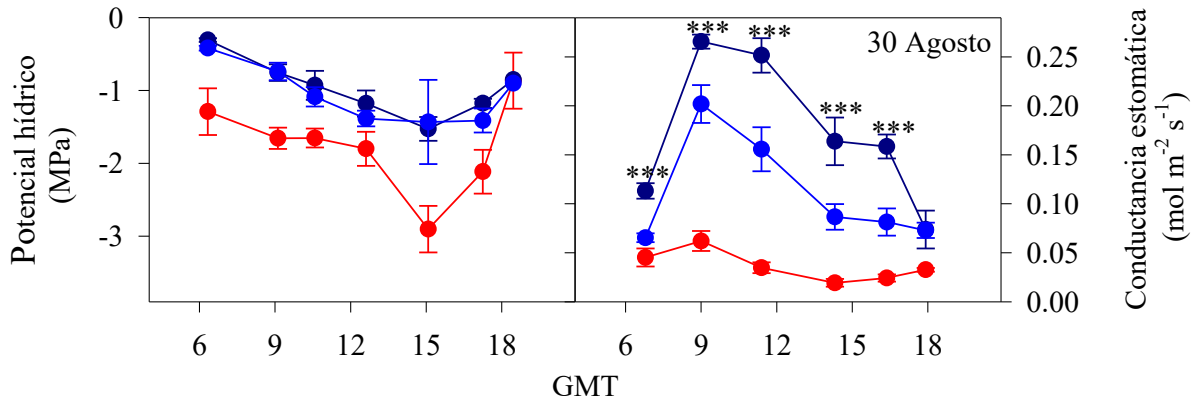
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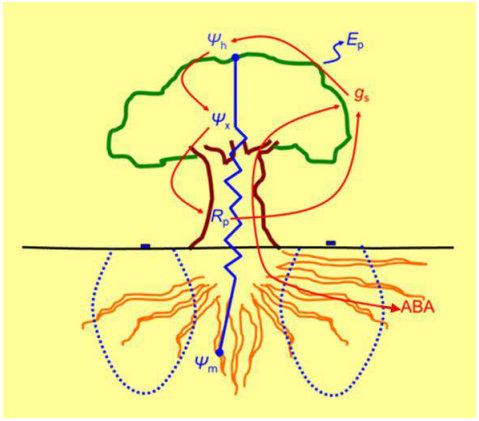
Fraction of the root zone wetted by irrigation

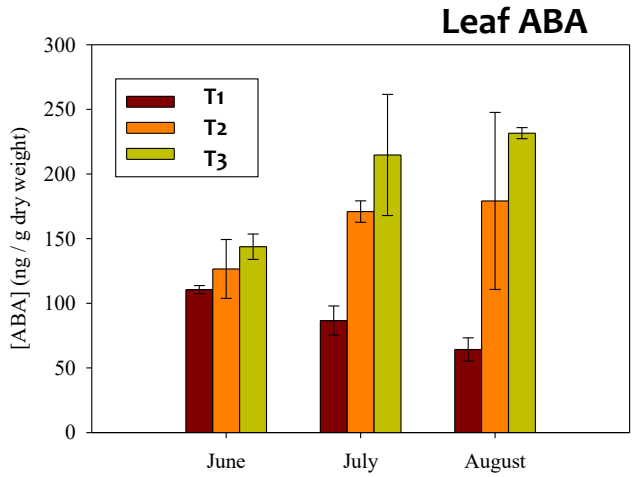




T3. Dry-farming







M.V. Cuevas et al. / Agricultural Water Management 97 (2010) 1293–1302

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Drying fractions of the root zone reduce transpiration





35 year-old 'Manzanilla' olive trees planted at 7 m × 5 m (El Aljarafe, Seville, Spain)

Root zone volume: 25 m^3.
Fraction of the root zone wetted by irrigation: 7-10 m^3 (20-30 %).

E_p increased ca. 35 % when the whole root zone was wetted:

- Less hydraulic resistance in the soil and soil-root interface.
- Lower stomatal control of transpiration because the root-to-shoot signaling mechanism disappeared.

These results means that the E_p of fully irrigated trees under localized irrigation is lower than the maximum potential E_p.

This means a FI treatment applied with localized irrigation is a Deficit Irrigation treatment.

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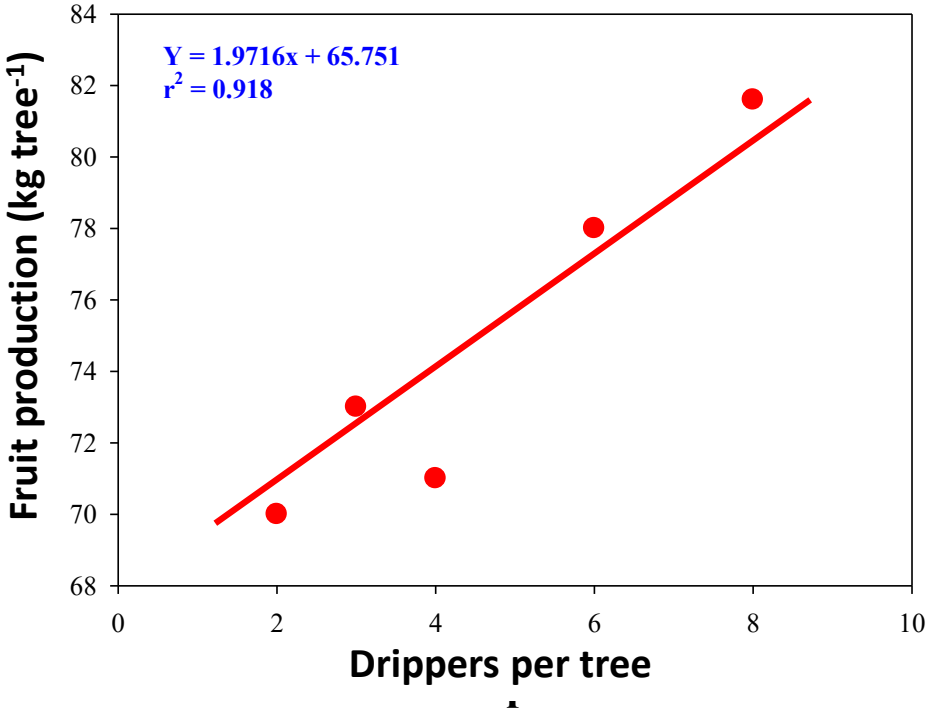
Drying fractions of the root zone reduce transpiration

Localized irrigation helps to control excesive growth in super-high density fruit tree orchards.



Gispert, J.R., Ramírez de Cartagena, F., Villar, J.M., Girona, J., 2013. Wet soil volume and strategy effects on drip-irrigated olive trees (cv. 'Arbequina'). Irrigation Science 31 (3), 479-489.

The number of emitters per tree is important: Yield increases with the fraction of wetted root zone.

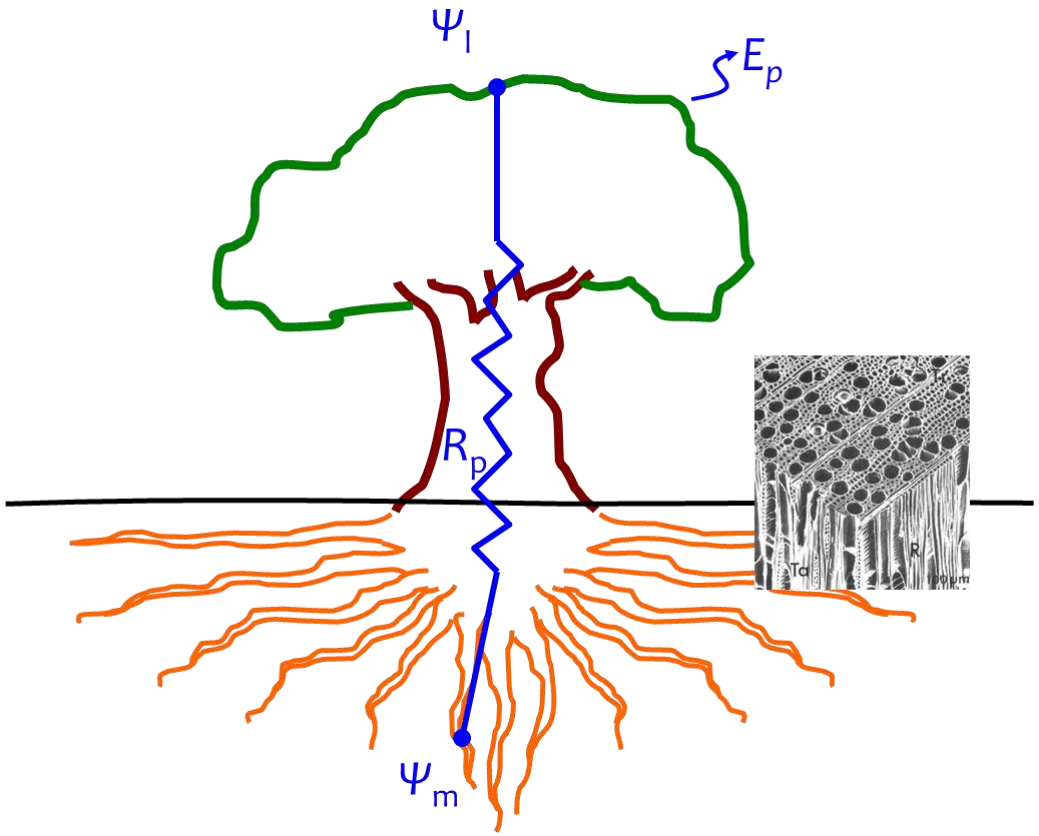


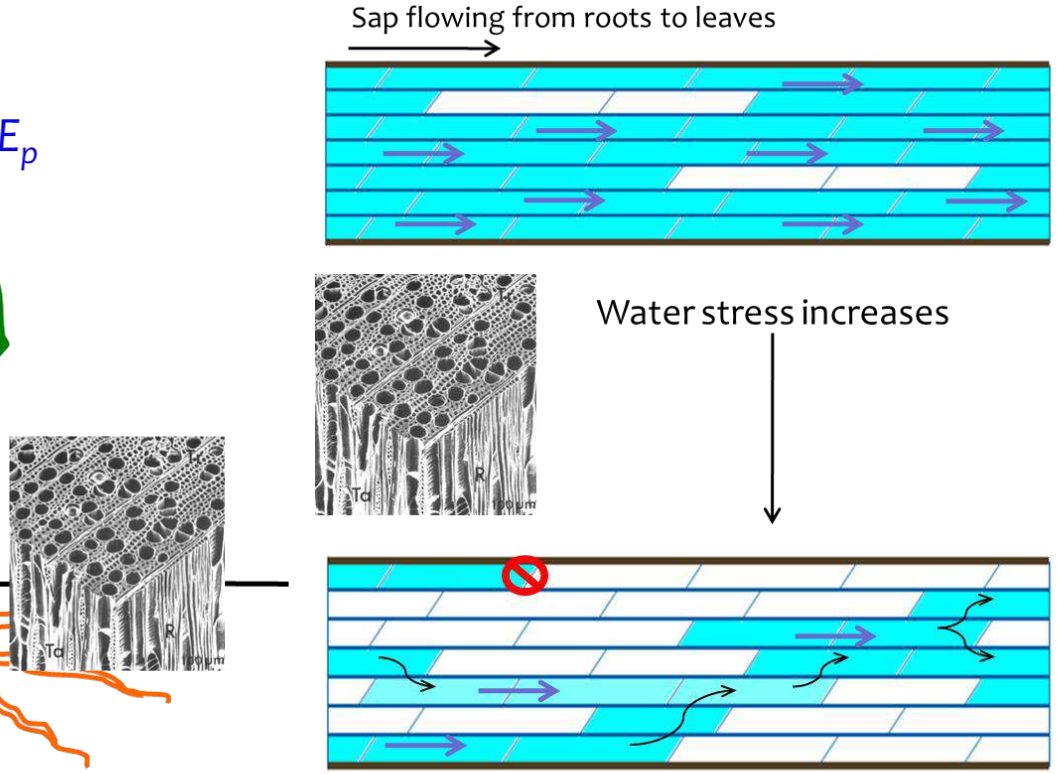
SOURCE: M. Pastor et al., 2005. Ensayos en plantaciones de olivar superintensivas e intensivas. Vida Rural 218, 30-40.

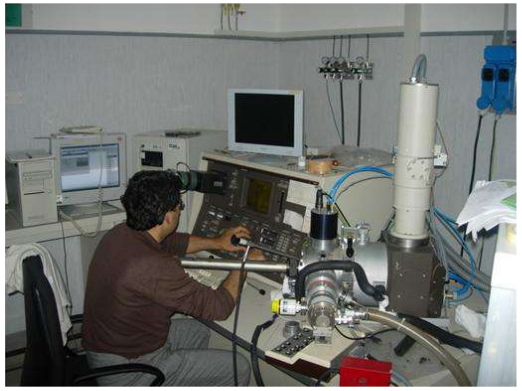
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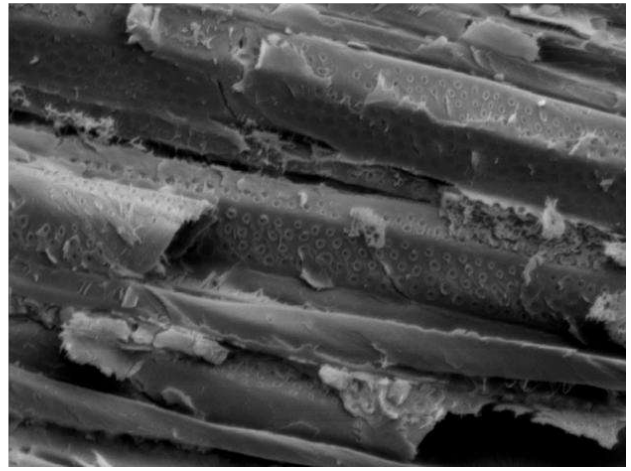
Resistance to embolism

The olive tree is able to maintain the functionality of its hydraulic system under severe water stress.







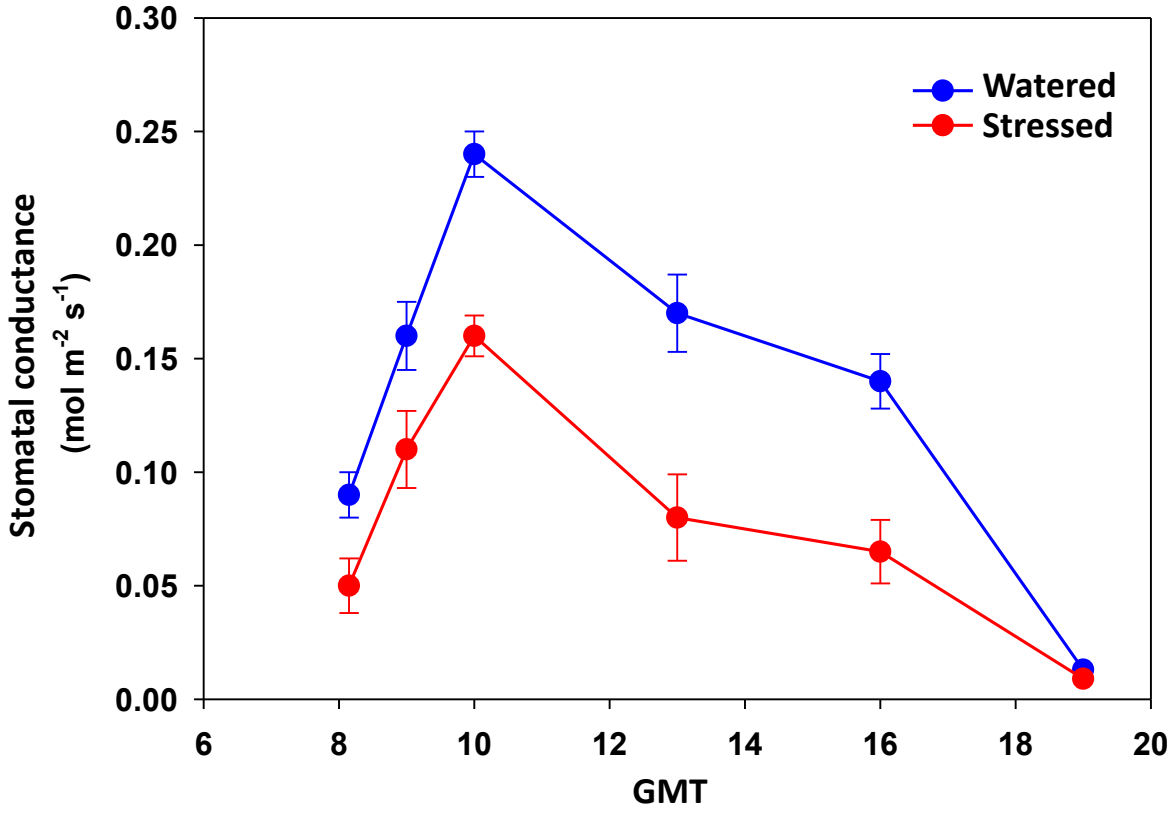


The functionality of the xilem remains even under severe water stress

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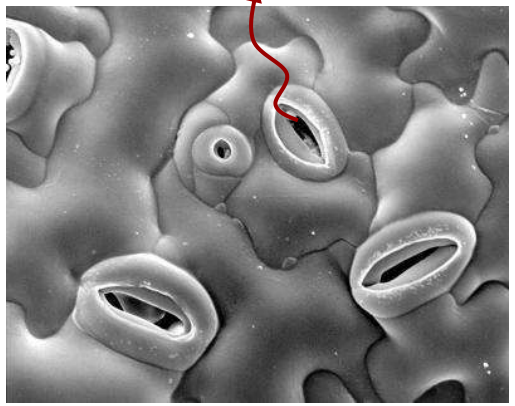
Stomata control of transpiration

The stomata of the olive tree close early in the day to avoid excessive plant dehydration. This helps to maintain the functionality of the conductive system. In addition, stomatal opening is reduced in water-stressed plants.





H_2O

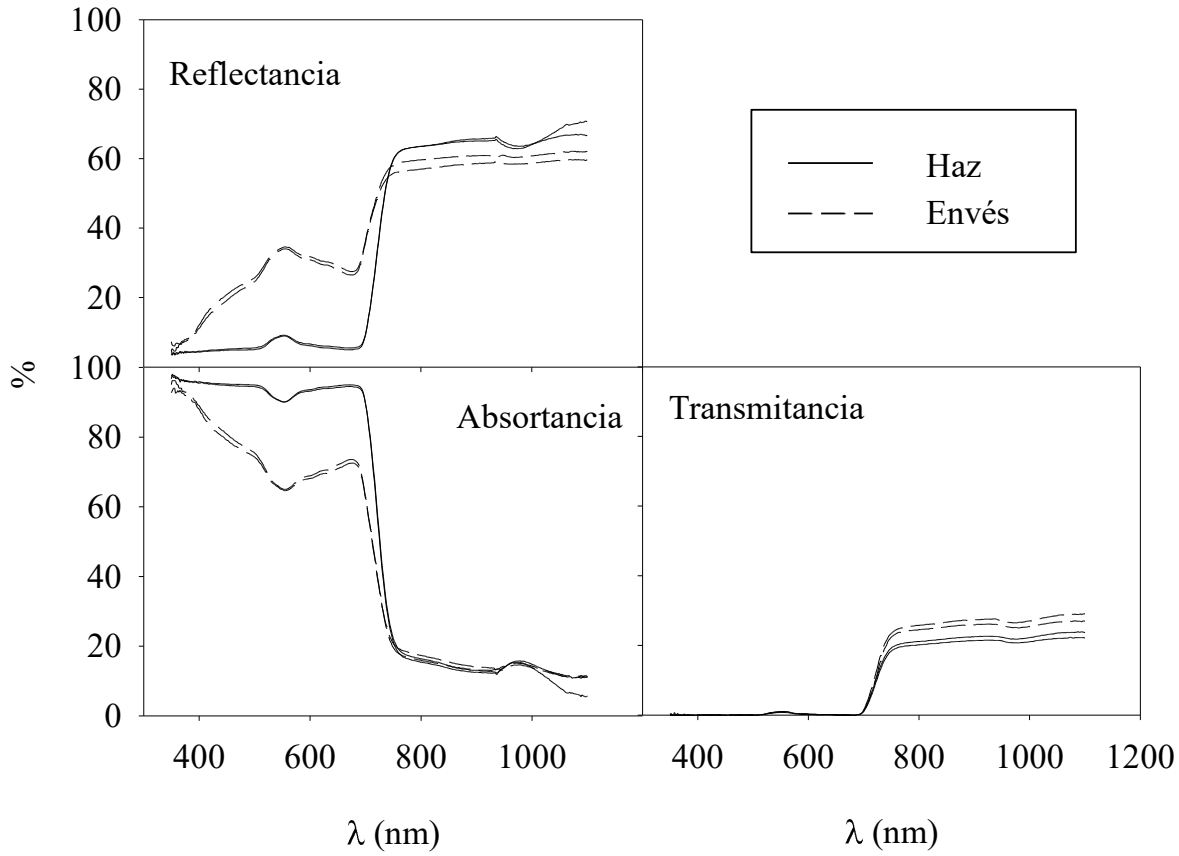


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Leaf adaptations to water stress



The underside (abaxial side), reflects better the radiation tan the upper side (adaxial side).



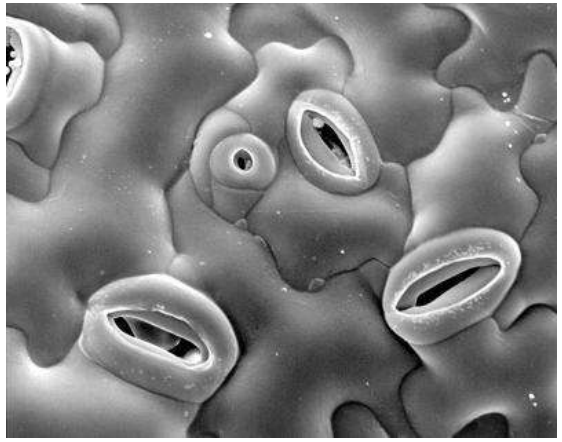
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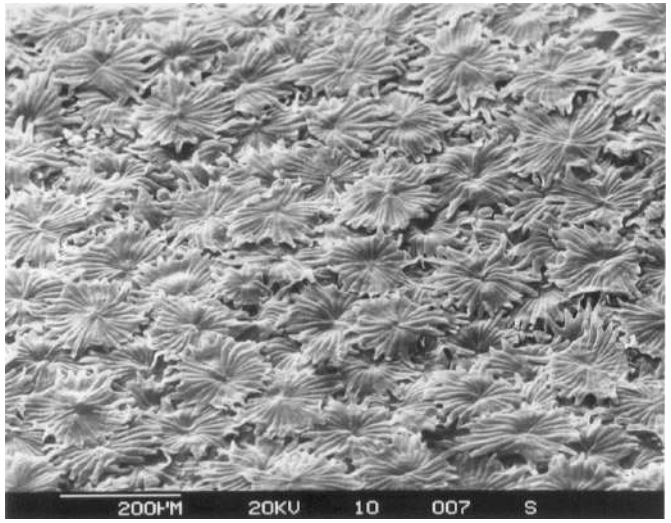
Leaf adaptations to water stress

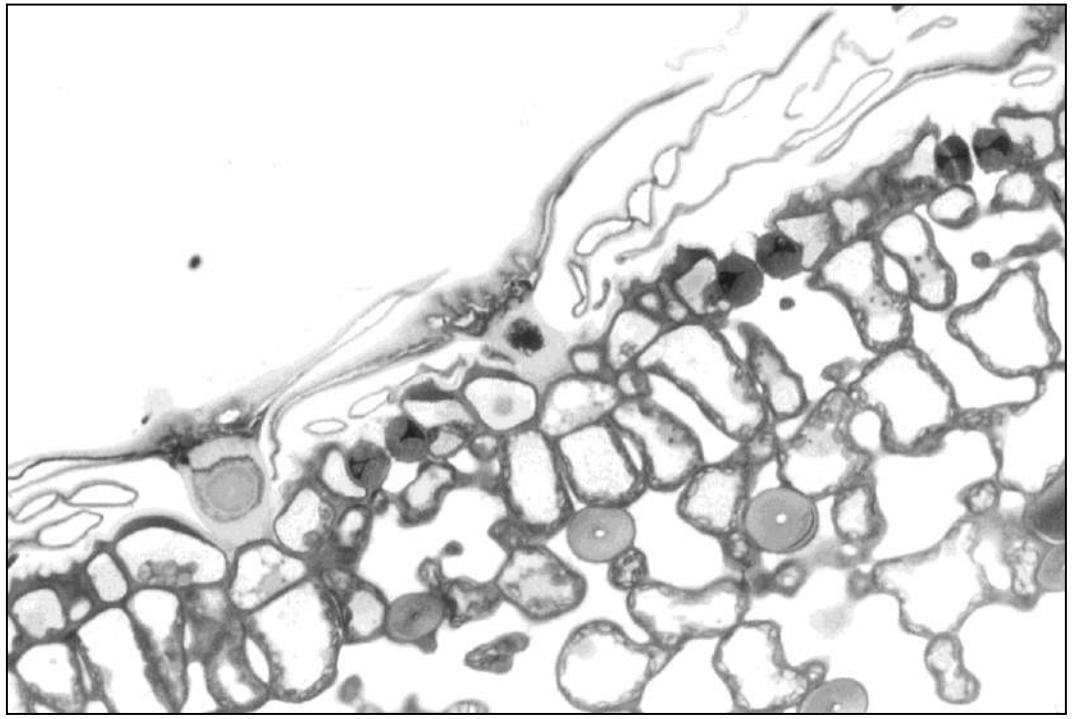
The abaxial side is waterproof, and it has les stomata tan the adaxial side.

The stomata of the adaxial side are protected by thrichomas.









(Photos: Dr. A. Díaz)

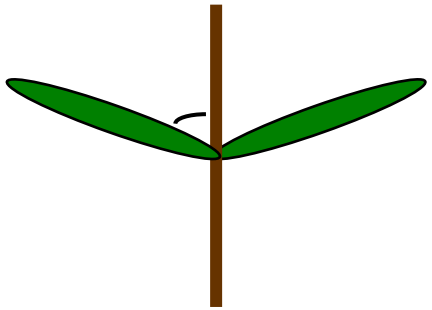
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Leaf adaptations to water stress

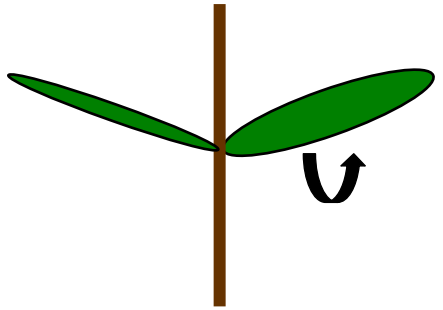




The leaf-shoot angle decreases with increasing water stress.



The leaf rotates to be less exposed to solar radiation.



These leaf movements allow the stressed plants to receive less solar raditation.

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Impact of reduced irrigation

Reduced irrigation affects g_s earlier tan A_N, and growth more than yield

Plant Biosystems, Vol. 142, No. 1, March 2008, pp. 130–137

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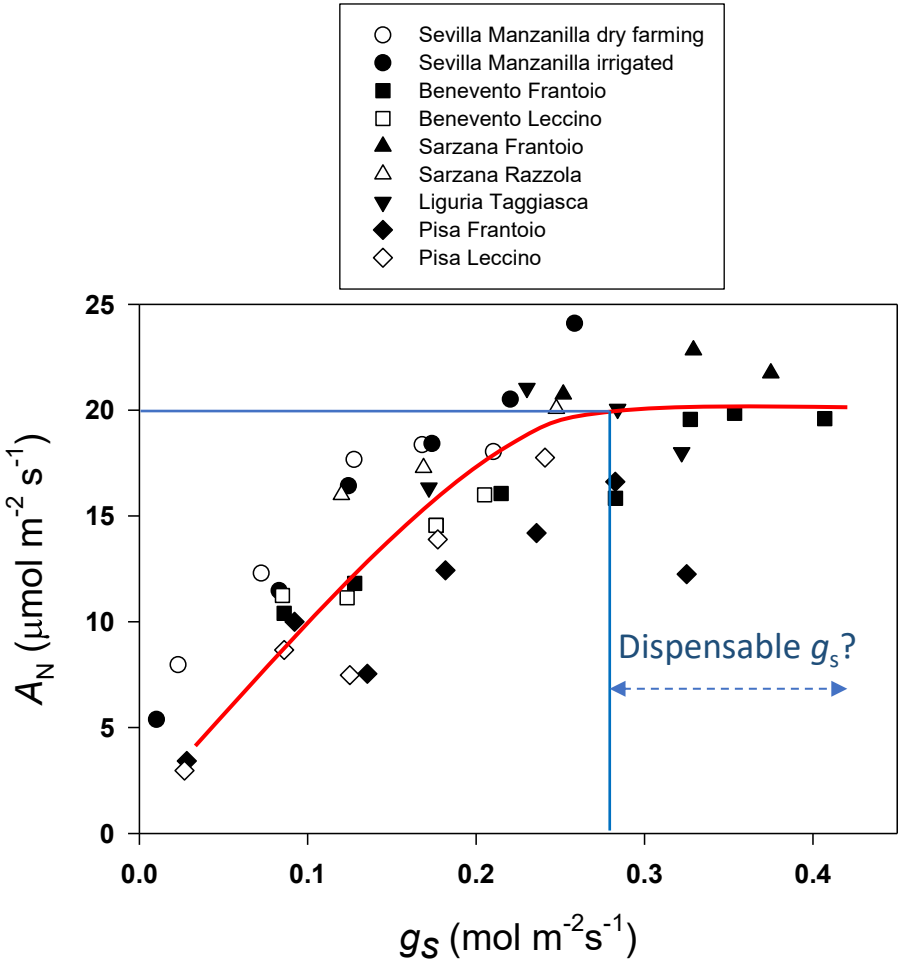
WATER RESOURCES IN MEDITERRANEAN BASIN

Potential and limitations of improving olive orchard design and management through modelling

JOSÉ ENRIQUE FERNÁNDEZ[1], ANTONIO DIAZ-ESPEJO[1], RICCARDO D'ANDRIA[2], LUCA SEBASTIANI[3] & ROBERTO TOGNETTI[4]

[1]*Instituto de Recursos Naturales y Agrobiología (CSIC-IRNASE), Spain,* [2]*Istituto per i Sistemi Agricoli e Forestali del Mediterraneo (CNR-ISAFoM), Italy,* [3]*Biolabs, Scuola Superiore Sant'Anna di Studi Universitari e di Perfezionamento, Italy, and* [4]*Dipartimento di Scienze e Tecnologie per l'Ambiente e il Territorio (STAT), Università degli Studi del Molise, Italy*

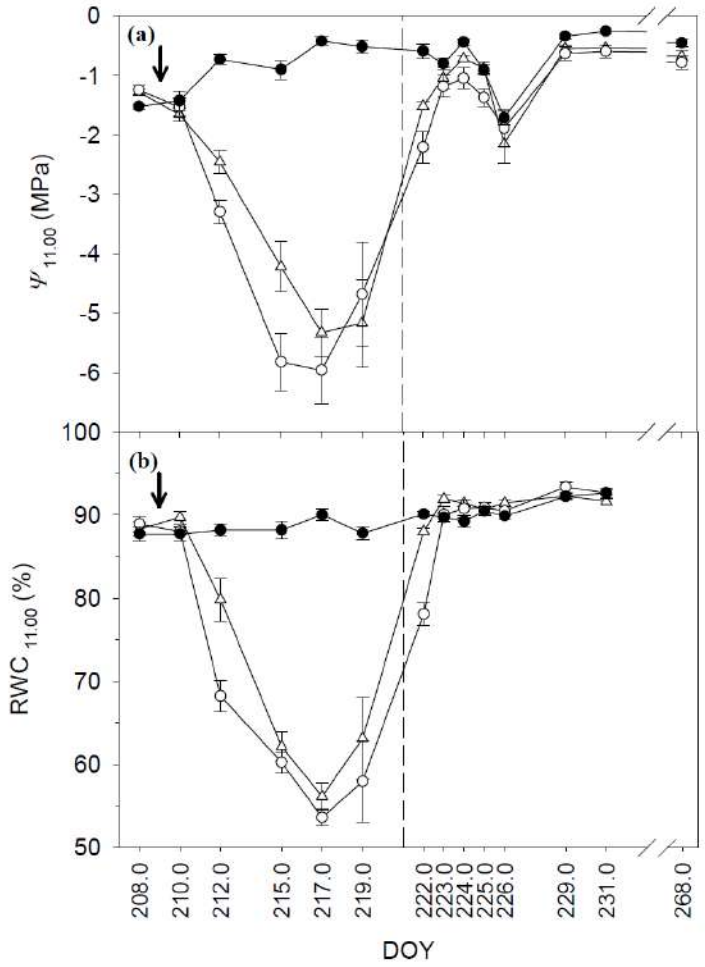
Could we reduce irrigation to reduce g_s withouth affecting crop performance?

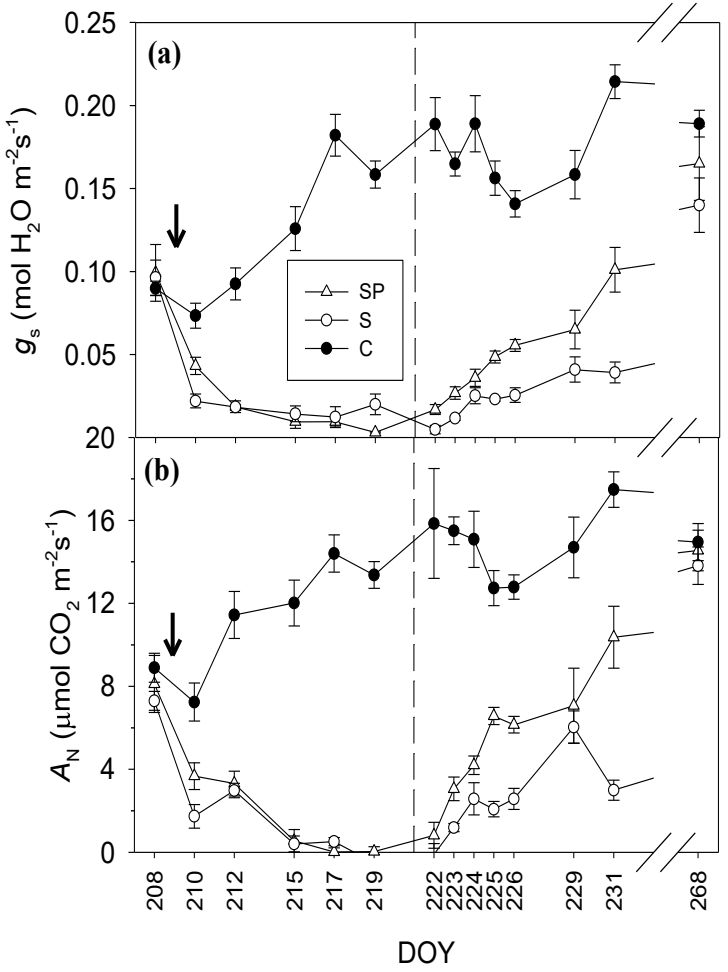


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Recovery after a period of water stress

Ψ_{leaf} recovers quickly. Both g_s and A_N take longer to recover.





Journal of Experimental Botany, Vol. 65, No. 12, pp. 3143–3156, 2014
doi:10.1093/jxb/eru160 Advance Access publication 5 May, 2014
This paper is available online free of all access charges (see http://jxb.oxfordjournals.org/open_access.html for further details)

RESEARCH PAPER

Regulation of photosynthesis and stomatal and mesophyll conductance under water stress and recovery in olive trees: correlation with gene expression of carbonic anhydrase and aquaporins

Alfonso Perez-Martin[1,*], Chiara Michelazzo[2,*], Jose M. Torres-Ruiz[1], Jaume Flexas[3], José E. Fernández[1], Luca Sebastiani[2] and Antonio Diaz-Espejo[1,†]

Caution is required when using $\Psi_{leaf/stem}$ measurements to assess water stress.

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Fundamentals of Irrigation

1. Water in the soil

2. The agrometeorological station

3. Plant-based measurements related to water stress

4. Physiological mechanisms related to water stress

5. Agronomic performance

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Growth

Plant height: Specially applicable to herbaceous plants.

Shoot lenght: Recommended for woody plants. Depending on the species, it can be time and labour consuming. Results can be highly variable, due to different growth rates for different types of shoots in the same plant.

Number and length of internodes: These variables refer to the impact of water stress on plant development. Reduced irrigation, for example, can cause reduced internode length.

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Leaf area

It can be measured with different methods:

- Manually: graph paper methods, weight paper method.
- Mobile apps: Viticanopy, Petiole Pro, Petiole App, Easy Leaf Area, etc.
- With leaf area meters:



CI-202 Portable Laser Leaf Area Meter
CID-BioScience



LI-3000C Portable Leaf Area Meter
LI-COR



LI-3100C Leaf Area Meter
LI-COR



LAI-2200C Plant canopy analyzer
LI-COR

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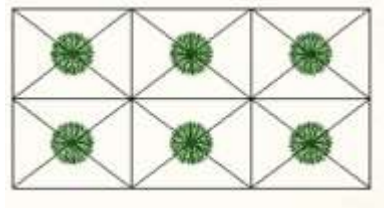
Leaf area

It can be measured with different methods:

- With allometric relationships: Ø shoot/branch vs. supported leaf area.

  In this case, we must take into account the area of the leaves fallen during the considered period. Otherwise, we will overestimate LA.

Watch out! The leaf area index (LAI) can be calculated in two different ways:



- LAI as m^2 of leaves per m^2 of soil corresponding to each tree within the orchard

- LAI as m^2 of leaves per m^2 of soil covered by the canopy



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Yield and quality

Yield: Is the marketable production, i.e., the fraction of the production that the grower can sell.

Production: Includes the yield plus the fraction of the production that cannot be sold because of poor quality, low harvesting efficiency, etc.

The yield to be taken into account is not always directly related to the fruit yield. This is the case of the olive tree for oil production, since the oil yield depends not only on the weight of the harvested fruits, but also on the oil content (%) and oil extractability (%).

Yield quality: when the grower is paid by both yield and quality, main variables related to the latter must be considered. For example, for olive oil production we can consider acidity, contents of different phenolic compounds including carotenoids and chlorophylls, coefficients of specific extintion at 232 nm and 270 nm (K_{232} and K_{270}), etc.

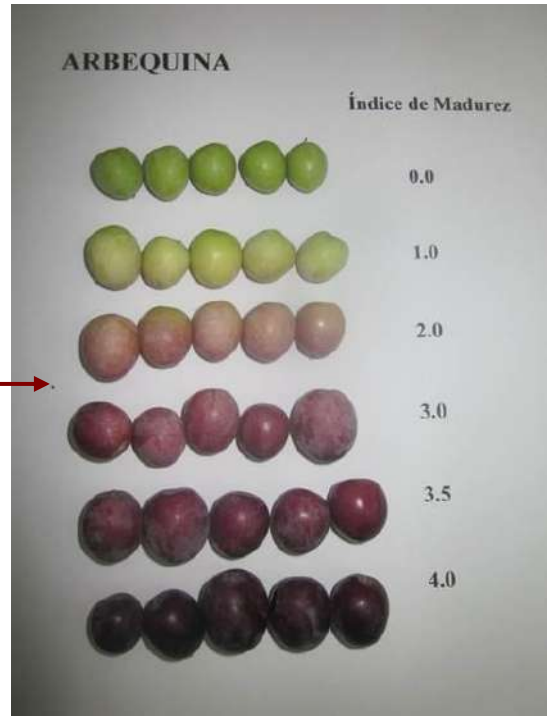
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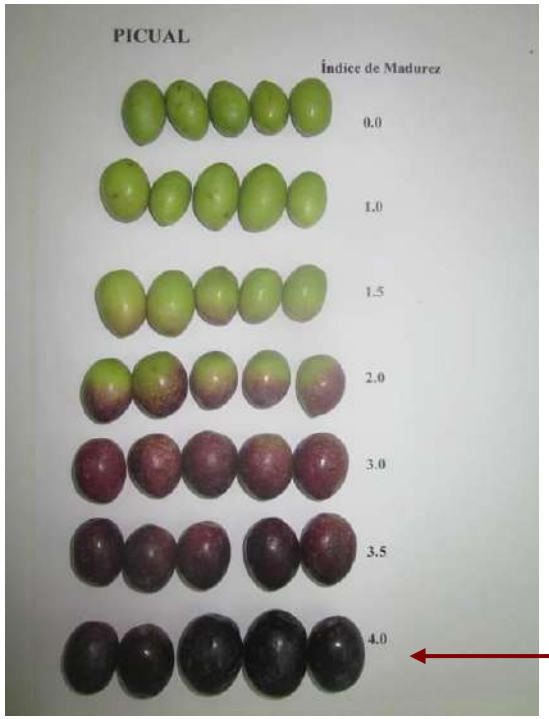
Yield and quality

The harvesting date: It has to be chosen with care, because it may affect the yield and quality results.

Maturity Index

Best quality oil
(October)





Best quality oil
(December)

The 'Picual' cultivar produces bitter oil than 'Arquina': for M.I. = 4, the oil is less bitter tan for M.I. = 2-3.

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The Production Function

The 'average' production function

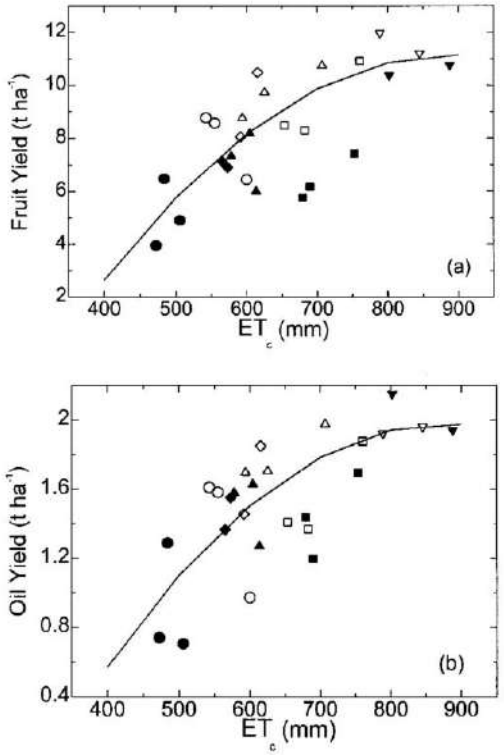


Fig. 7. Relationship between a) fruit yield (t·ha^{-1}) and b) oil yield (t·ha^{-1}) against olive evapotranspiration (ET_c, mm). Points represent yield and ET_c biennial averages for each replicate plot. Empty symbols correspond to 1997–98, while full symbols correspond to 1998–99 for CON (▽, ▼); RDI (◊, ♦); SDI (Δ, ▲); AYI (❑, ■); and DRY (○, ●) treatments. The best fit relationships are (**a**) for yield; $Y = -16.84 + 0.063\ ET - 0.035 \times 10^{-3}\ ET^2$; $R^2 = 0.71$; $P < 0.001$; RMSE = 1.2; n = 23 and (**b**) for oil; $Y = -2.78 + 0.011\ ET - 0.006 \times 10^{-3}\ ET^2$; $R^2 = 0.59$; $P < 0.001$; RMSE = 0.3; n = 23. The three data points of the AYI treatment in 1998/99 were not included in the regression analyses. For explanation see text.

SOURCE: Moriana et al. (2003)
https://doi.org/10.21273/JASHS.128.3.0425

The 'upper boundary 90%' production function

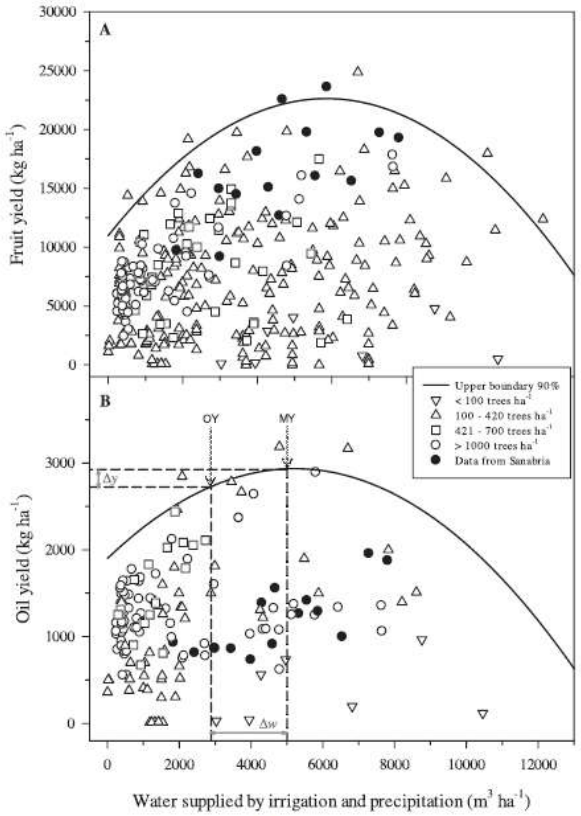


Fig. 1. Fruit yield (A) and oil yield (B) versus seasonal water supplied by irrigation and precipitation in olive orchards of the Mediterranean basin, with different plant densities. Data are from 24 orchards including 'Sanabria', the hedgerow olive orchard considered in the case study of Section 3. The upper boundary was adjusted to the 90 % of yield data points. In Graph B, Δw and Δy represent the portions of water supplied and oil yield, respectively, from the points of the upper boundary at which the optimal yield (OY) and the maximum yield (MY) are achieved (see Section 2.2 for details). Both Δw and Δy are a conceptual representation, such that the actual OY and MY values would depend on the conditions of every orchard.

SOURCE: Fernández et al. (2020)
https://doi.org/10.1016/j.agwat.2020.106074

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Irrigation Strategies



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Definitions related to irrigation

IRRIGATION SCHEDULING refers to the calculation of the amount of water to be applied at each irrigation event, and on when to apply it. There is a variety of irrigation scheduling methods, based on soil water, atmospheric demand and/or plant-based measurements.

The term IRRIGATION STRATEGY refers to both how much water we are going to apply and to the timing of irrigation.

If we use **Full Irrigation**, it means we are going to replace the water demanded by the crop, with frequent irrigation events (usually daily, in case of localized irrigation).

The alternative to full irrigation is **Deficit Irrigation**. The following deficit irrigation strategies have been defined: supplementary or complementary irrigation, low frequency irrigation, sustained deficit Irrigation, partial rootzone drying, regulated deficit irrigation…

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Full irrigation

Full irrigation consists on replacing the water consumed by the crop.

FULL IRRIGATION:

$IN = ET_c - P_e$ Irrigation for non-limiting soil water conditions (ϑ_V close to FC)

For FI, the irrigation season must start at the end of the rainy season, when the soil is around FC. The irrigation amounts and irrigation frequency must allow for that level of soil water content to remain constant.

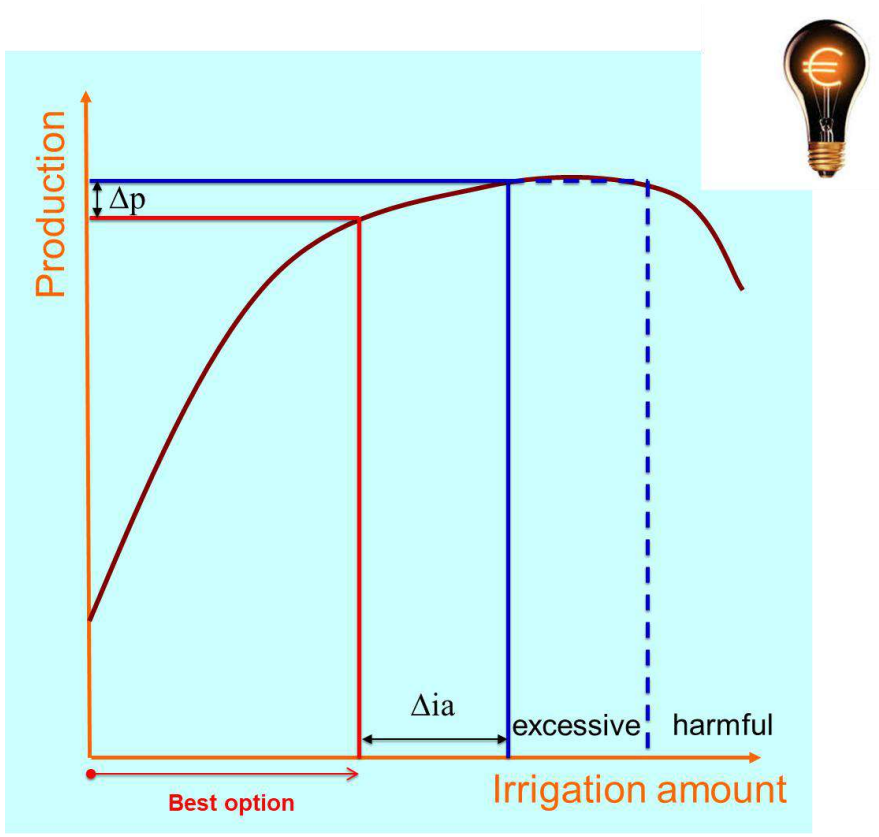
In fully irrigated crops with high plant densities, daily irrigation is usually required.

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Full irrigation

FI ensures maximum crop perfomance. But that does not mean that FI is the optimum strategy:

- We do not take advantage of the water stored in the soil
- If qualiyt is pursued, FI may not be advisable
- In SHD orchards FI may promote excesive growth and a greater incidence of diseases
- The cost of water and electricity may not advise for FI

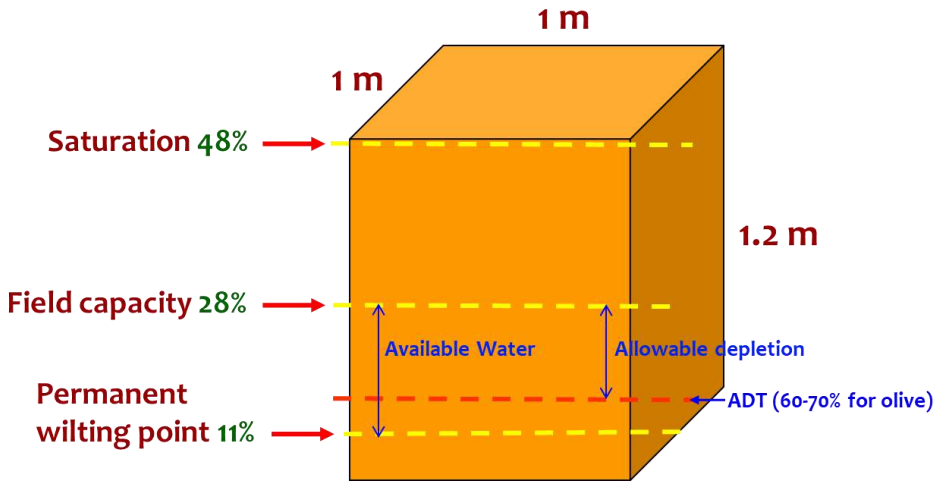


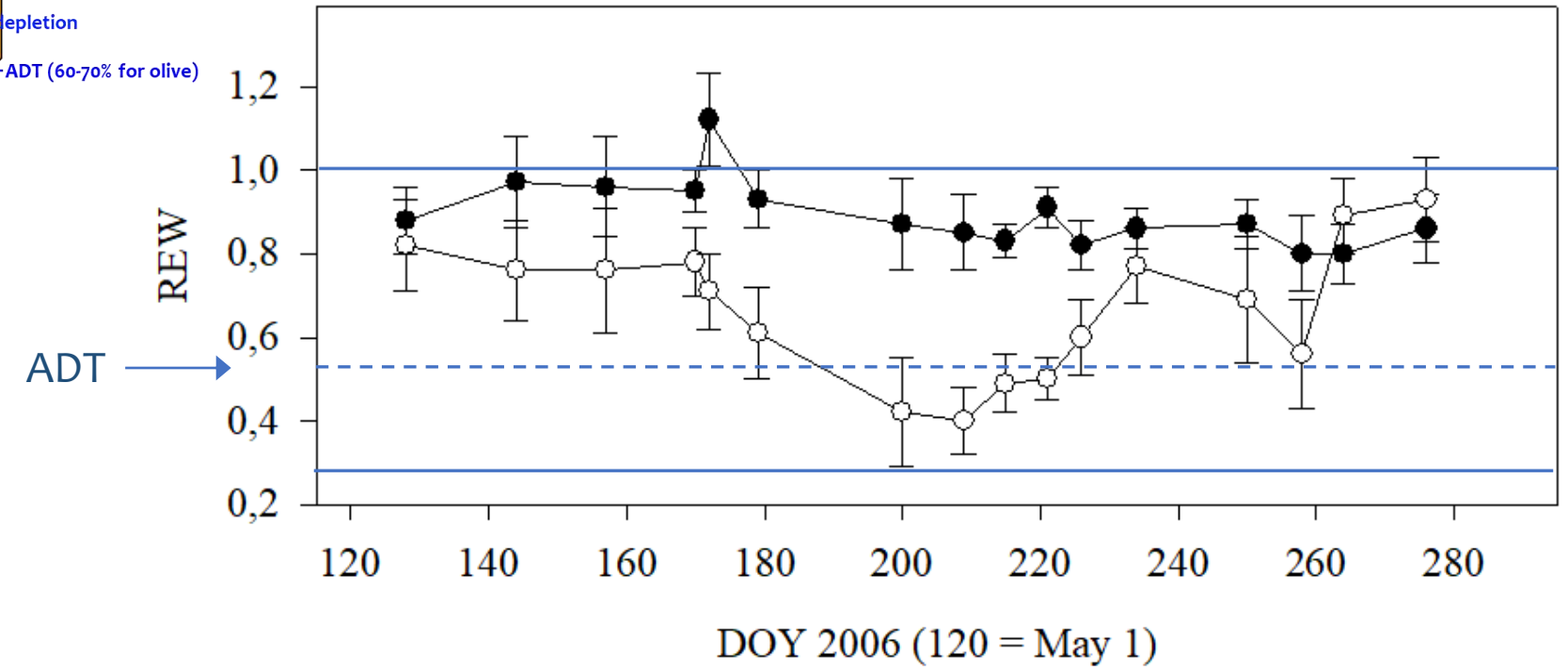
FI is advisable for new orchards, until the trees are well established: it shorthens up the period bewteen planting and full production

At the end of the presentation we will address the optimum irrigation

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Irrigation strategy which takes into account the water stored in the soil (the 'recommended' irrigation)

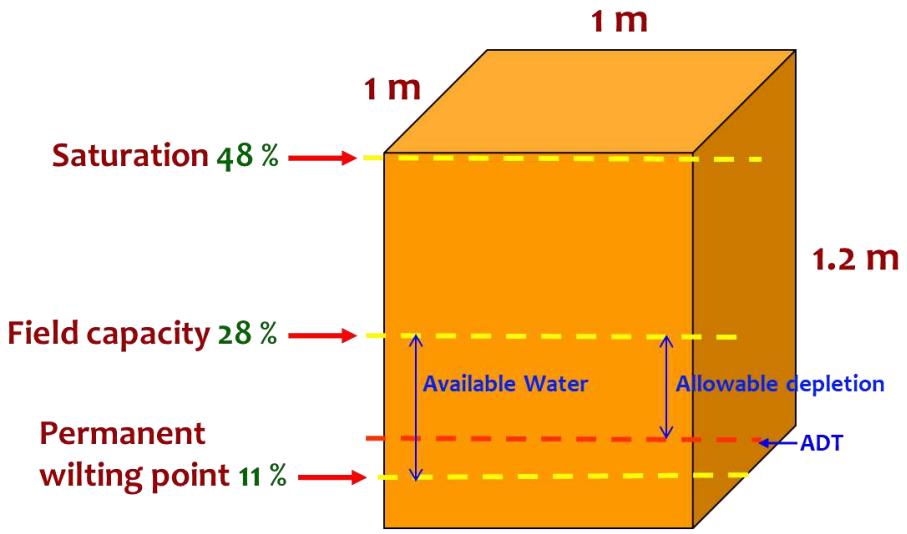




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The water stored in the soil must be taken into account when managing irrigation

Imagine that my crop requires 3800m³ ha⁻¹ of irrigation water



$IN = ET_c - P_e$ Irrigation for non-limiting soil water conditions (ϑ_V close to FC)

$IN = ET_c - P_e - AD$ Irrigation in areas where water is scarce*

* It may imply some 10 % yield reduction

AW = (0.28 - 0.11) × 1200 = 204 mm
AD = AW × ADT = 204 × 0.70 = 142,8 mm
142,8 mm = 1428 m³ ha⁻¹ = 38 % of 3800 m³ ha⁻¹

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The ‘recommended’ irrigation

$IN = ET_c - P_e - AD$

The allowable depletion (AD) is also known as the management allovable depletion (MAD)

Table 3. Management allowable depletions (MAD) and maximum root zone depths for selected crops.

Type of crop	*MAD**	*Maximum root depth (ft.)***
Cotton	0.65	3.3 – 5.6
Barley and oats	0.55	3.3 – 4.5
Maize	0.50 – 0.55	2.6 – 6.0
Sorghum	0.50 – 0.55	3.3 – 6.6
Rice	0.20	1.6 – 3.3
Beans	0.45	1.6 – 4.3
Soybeans	0.50	2.0 – 4.1
Alfalfa	0.50 – 0.60	3.3 – 9.9
Cool season – Turf grass	0.40	1.6 – 2.2
Warm season – Turf grass	0.50	1.6 – 2.2
Citrus	0.50	2.6 – 5.0
Walnut orchard	0.50	5.6 – 8.0
Carrots	0.35	1.5 – 3.3
Cantaloupes/watermelons	0.40 – 0.45	2.6 – 5.0
Lettuce	0.30	1.0 – 1.6
Onions	0.30	2.0 – 3.0
Potatoes	0.65	1.0 – 2.0
Sweet peppers	0.30	1.6 – 3.2
Cucumbers	0.50	2.0 – 4.0

* MAD values are for crop water use of 0.20 inch/day
** Root depths can vary with soil and other conditions. Effective root depth is usually shallower.
Source: Allen et al. (1998)

SOURCE: Oklahoma Cooperative Extension Service BAR.1537, by S. Datta, S. Taghvaeian ans J. Stivers, June 2017

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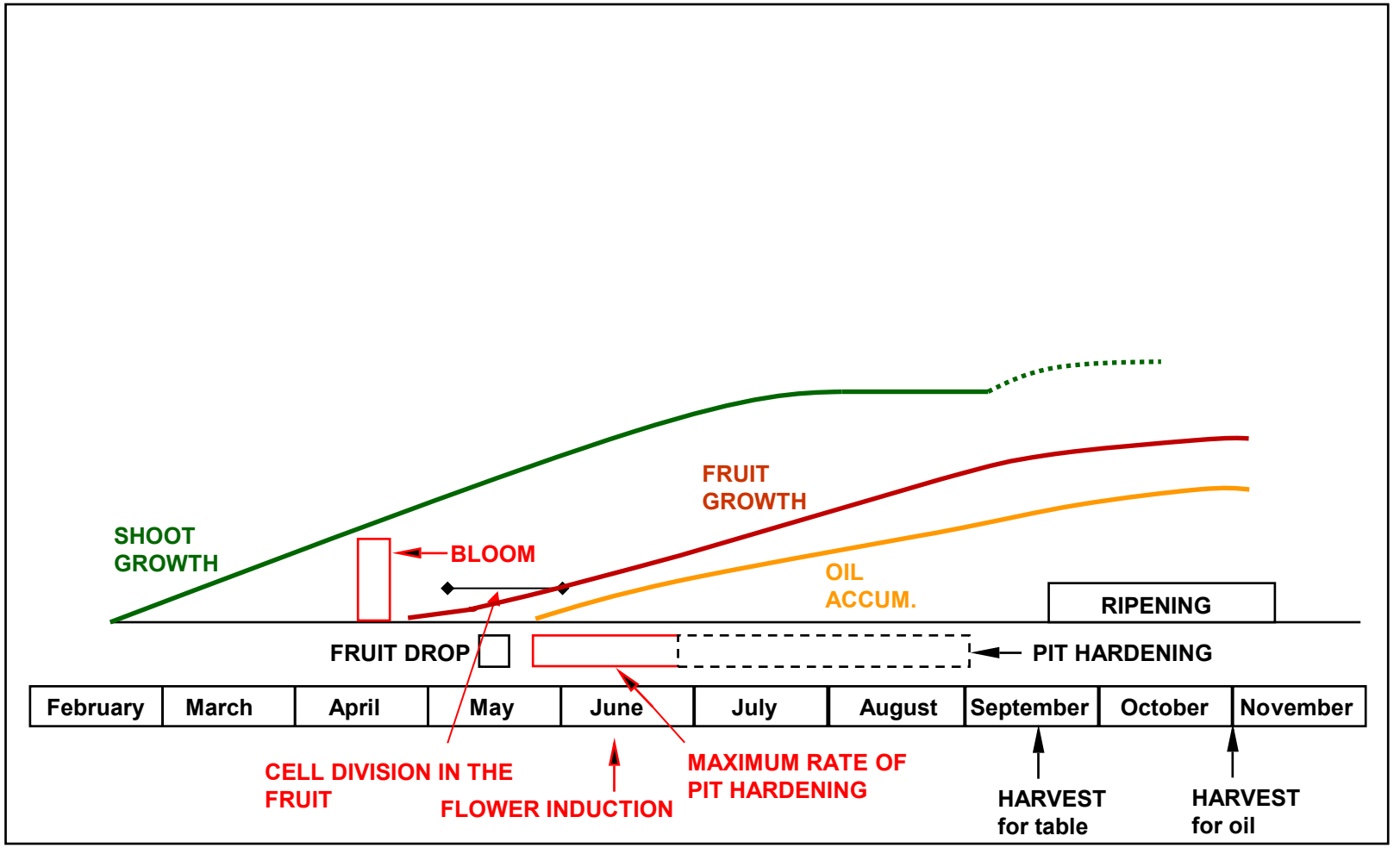
Full irrigation vs. 'recommended' irrigation

Crop	Full irrigation (m^3 ha^{-1})	Recommended Irrigation (m^3 ha^{-1})
Conventional Olive	3500	1500 (42 %)
SHD Olive	4500	3200 (71 %)
Almond	7000	5000 (71 %)
Citrus	6000	4000 (67 %)

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Deficit irrigation strategies

The olive growing cycle in SW Spain



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Deficit irrigation strategies

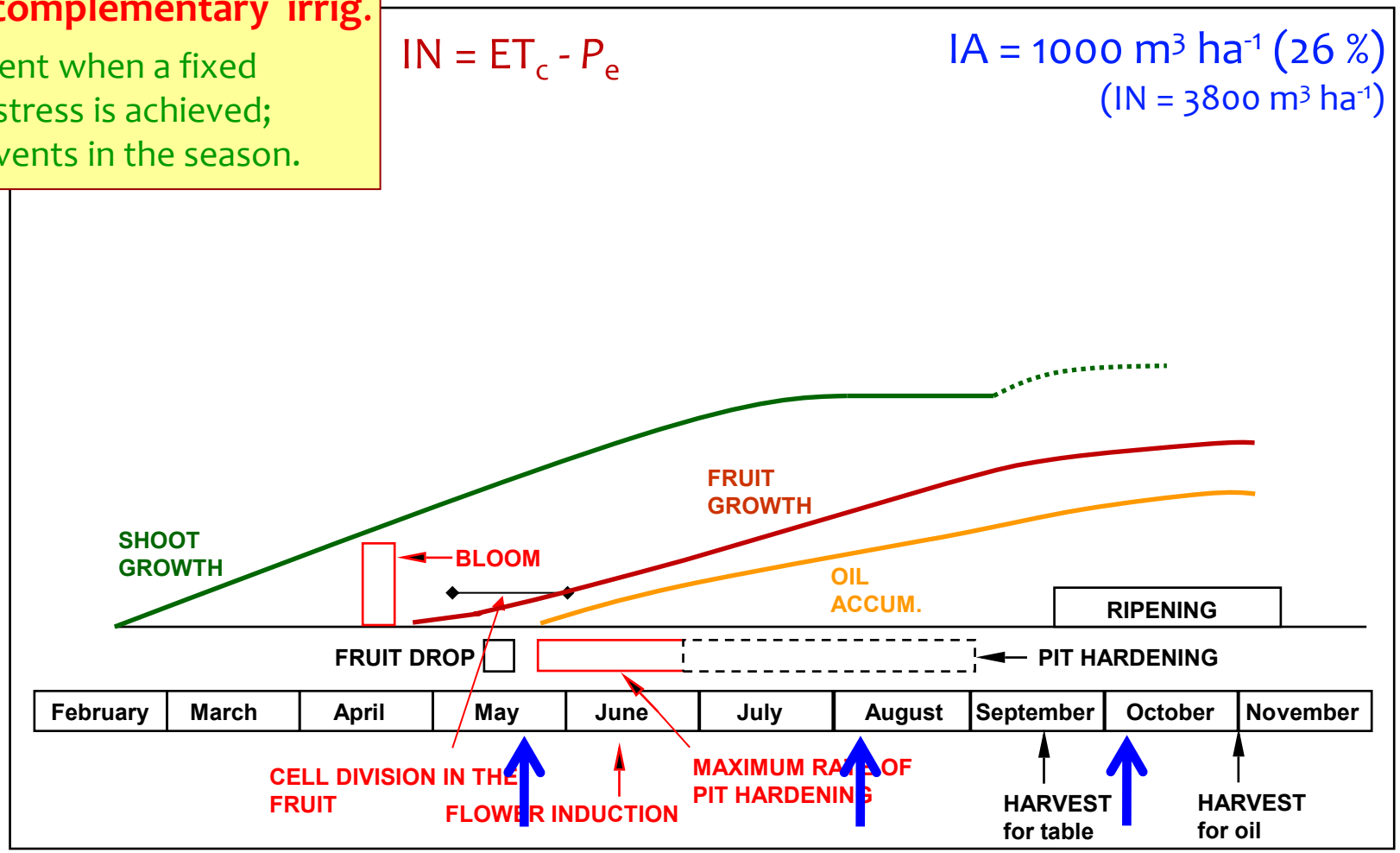
Suplementary or complementary irrig.

A single irrigation event when a fixed threshold for water stress is achieved; just 2 or 3 of these events in the season.

The olive growing cycle in SW Spain

$IN = ET_c - P_e$

$IA = 1000\ m^3\ ha^{-1}$ (26 %)
($IN = 3800\ m^3\ ha^{-1}$)



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Deficit irrigation strategies

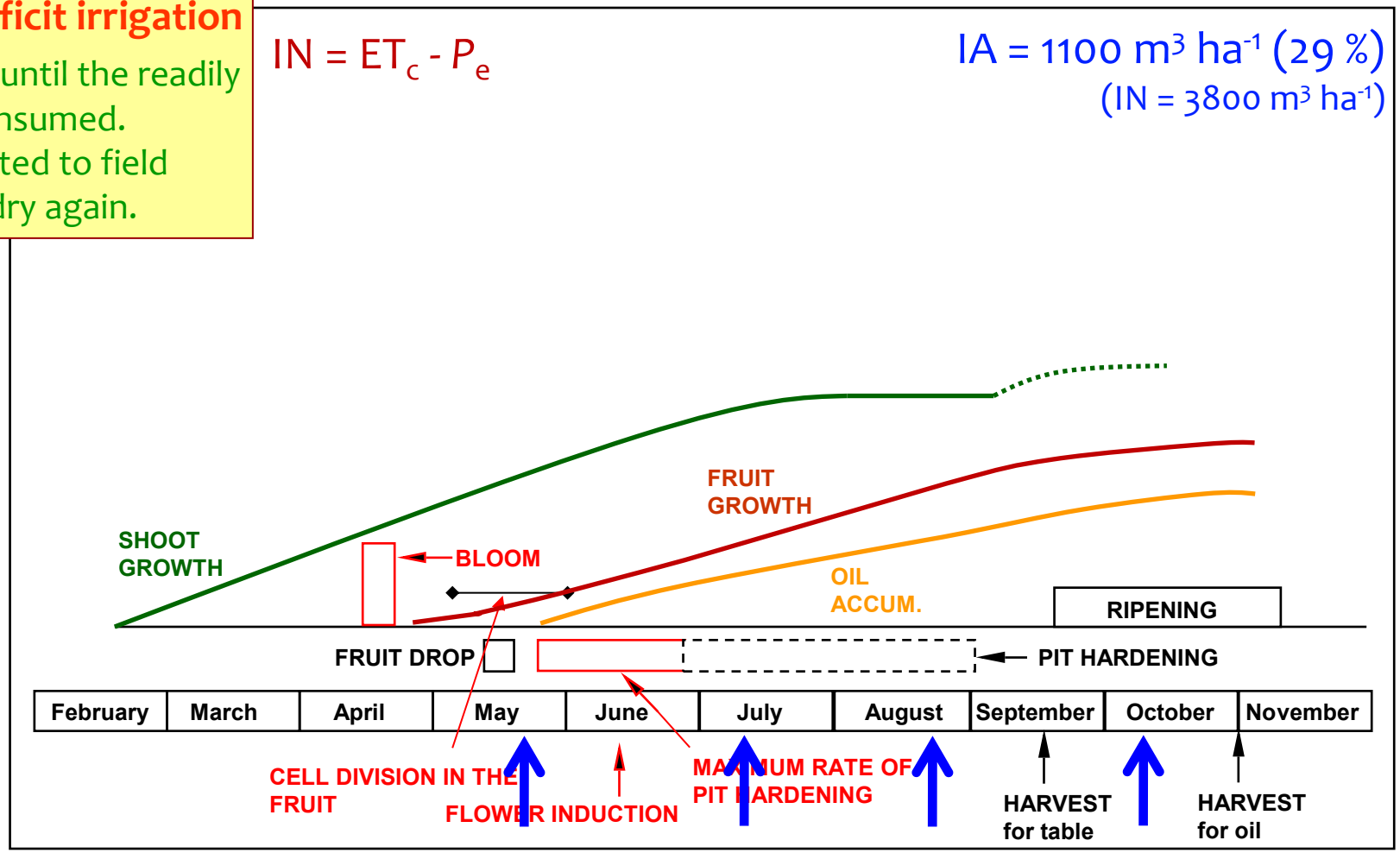
The olive growing cycle in SW Spain

Low frequency deficit irrigation

The soil is left to dry until the readily available water is consumed.
Then the soil is irrigated to field capacity and left to dry again.

$IN = ET_c - P_e$

$IA = 1100\ m^3\ ha^{-1}$ (29 %)
($IN = 3800\ m^3\ ha^{-1}$)



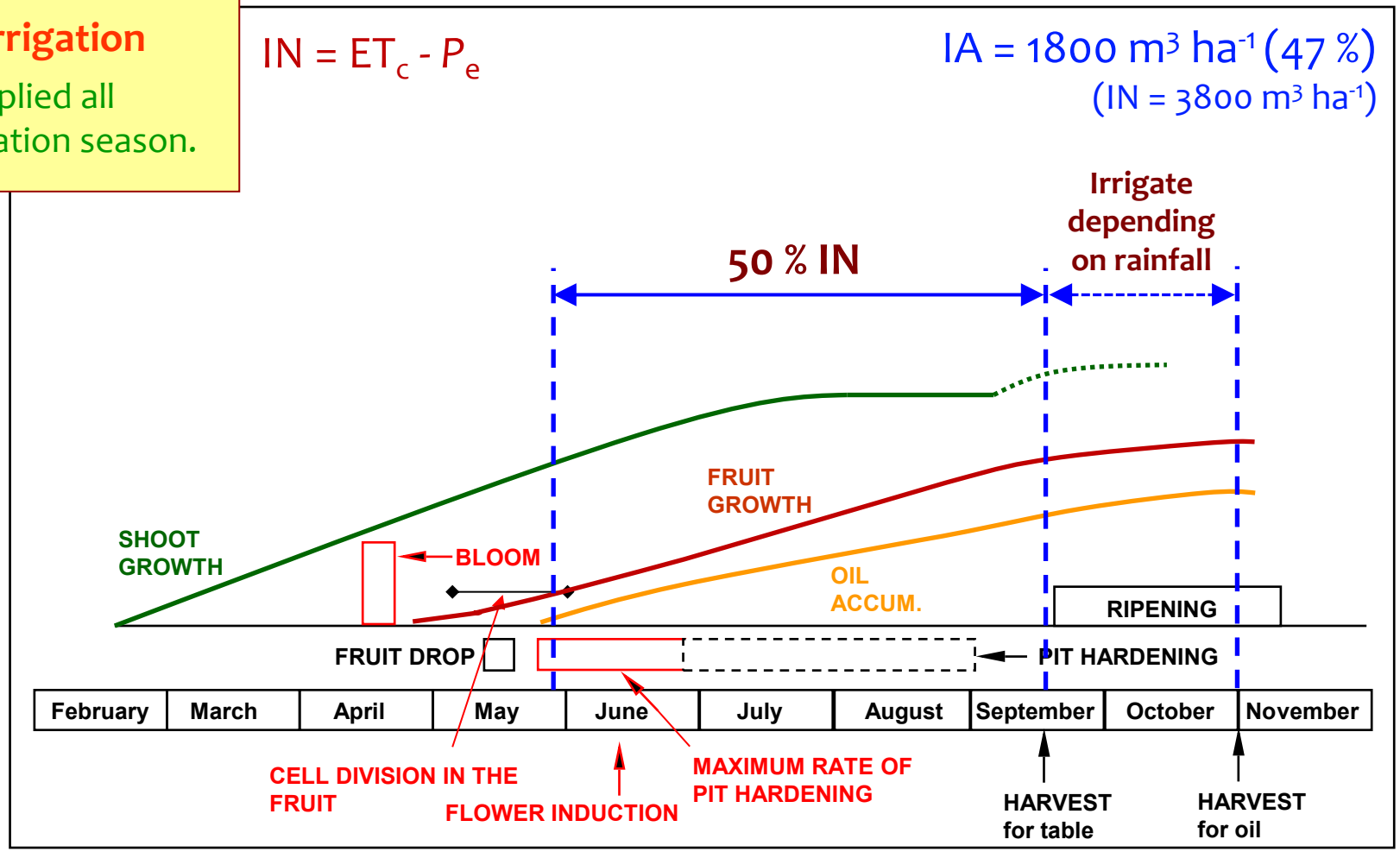
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Deficit irrigation strategies

Sustained deficit irrigation

A fraction of IN is applied all throughout the irrigation season.

The olive growing cycle in SW Spain



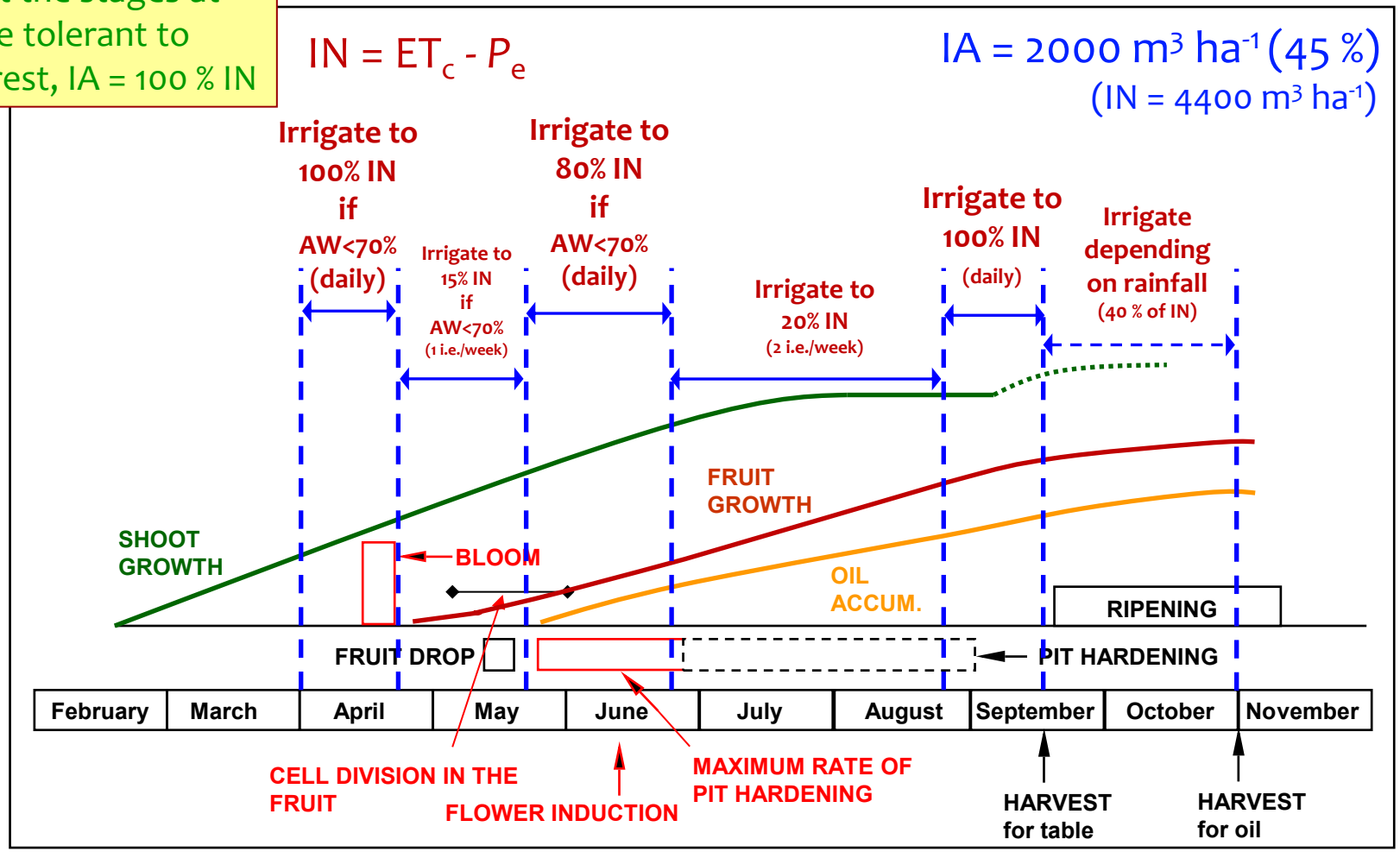
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Deficit irrigation strategies

Regulated deficit irrigation (RDI)

Irrigation is reduced at the stages at which the crop is more tolerant to water stress. For the rest, IA = 100 % IN

The olive growing cycle in SW Spain

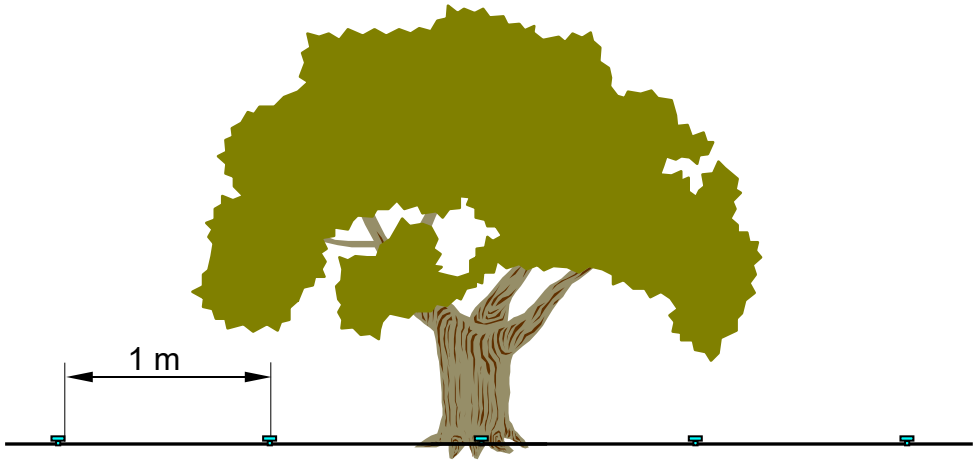


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Deficit irrigation strategies

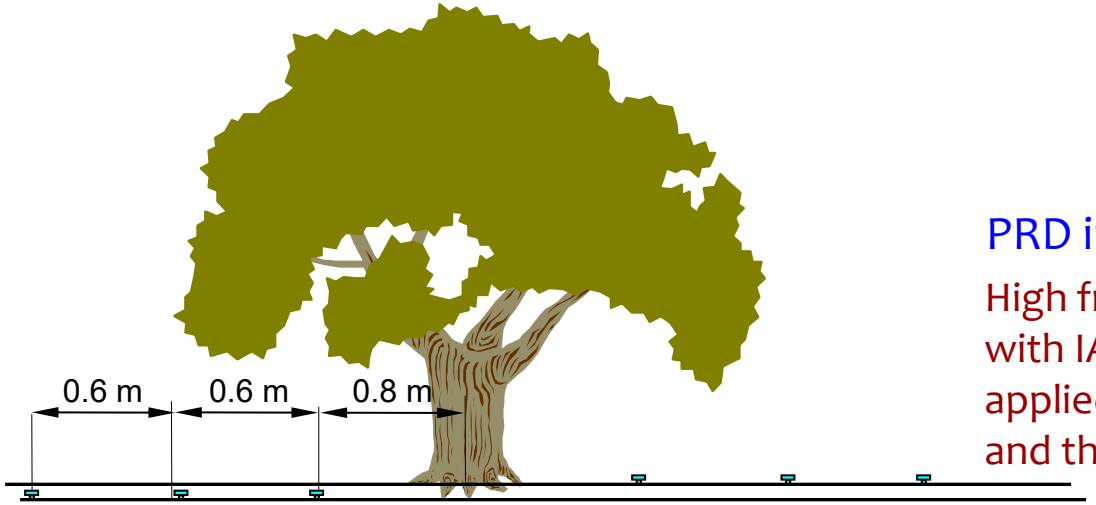
Partial rootzone drying (PRD)

$IA_{RDI} \approx IA_{PRD}$, but the water supply is switched from one side of the tree to the other every 2-3 weeks.



Sustained Deficit irrigation

High frequency irrigation
with IA = 50-70 % IN
applied to both sides of the tree



PRD irrigation

High frequency irrigation
with IA = 50-70 % IN
applied to one side for 2-3 weeks
and then shifted to the other side

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PRD does not work for woody plants in the field

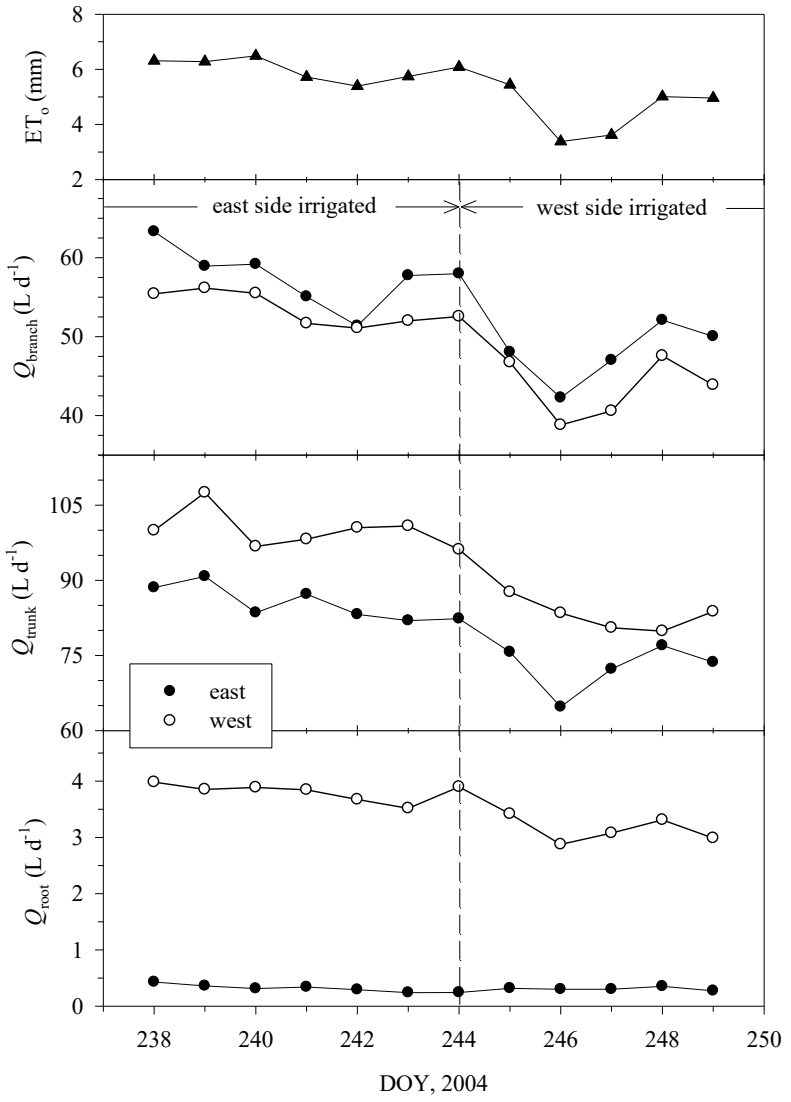




Under localized irrigation conditions, a fraction of the root remains under soil-drying conditions.

"The fraction of the root zone wetted by irrigation is related both to the effective soil water potential and to the triggering of root-to-shoot signaling mechanisms, which affect water status and water consumption by the tree" (Fernández, 2014).

Fernández, J.E., 2014. Understanding olive adaptation to abiotic stresses as a tool to increase crop performance. Environmental and Experimental Botany 103, 158-179.



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Advantages and disadvantages of Deficit Irrigation

Advantages:

- We save water, energy, labour…
- Qualiyt is improved
- Vigour is reduced (less pruning, lower impact of fungical diseases, longer lifespan of the orchard…)
- It may allow for subsidies

Disadvantages:

- It can be a problem in case of saline soils or saline water
- Its management is more demanding than that of FI, especially for RDI
- Mistakes in the irrigation management and malfunctions in the irrigation system can penalize crop performance

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RDI in a SHD olive orchard with decreasing IAs

The Sanabria orchard





'Arbequina' trees at 4 m × 1.5 m (1667 trees ha^{-1})

Production target:

- To achieve the most profitable equilibrium between yield and quality
- To control vigour
- Maximum orchard lifespan

Experimental period:

2010 (4 year-old trees) to 2013

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RDI in a SHD olive orchard with decreasing IAs

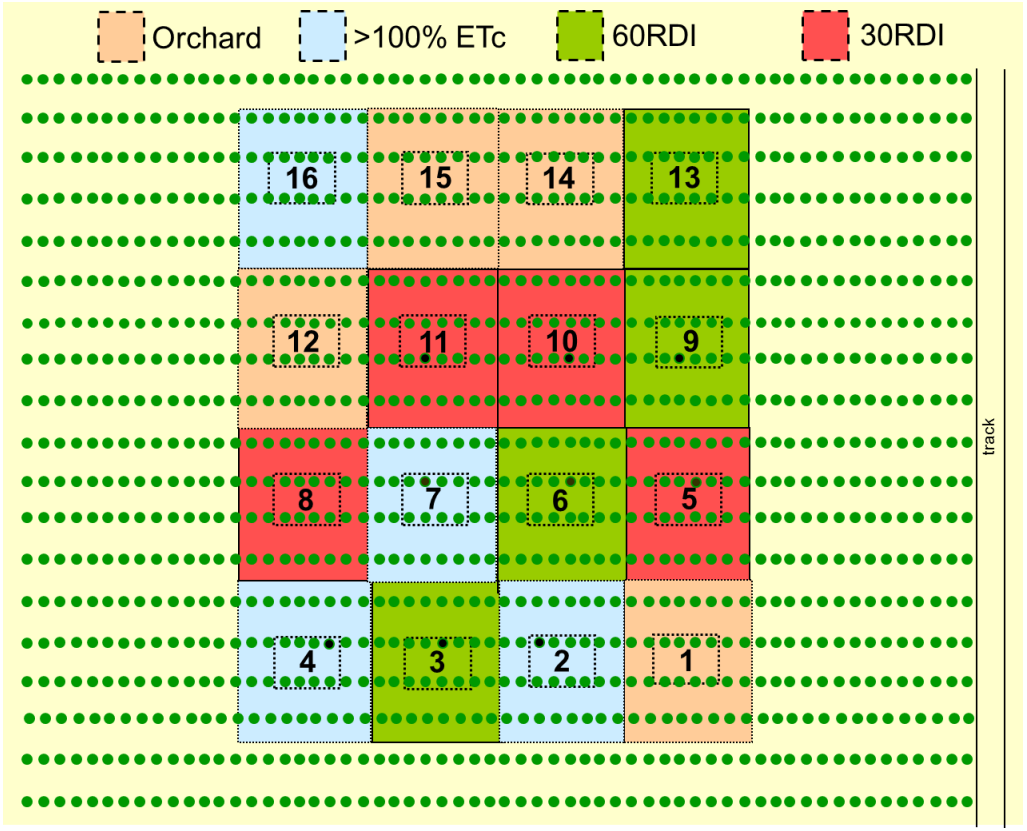








Randomized block design



Orchard (SDI)	**70 % IN**
100 % ET_c	**100 % IN**
60RDI	**60 % IN**
30RDI	**30% IN**







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RDI in a SHD olive orchard with decreasing IAs

Table 2. FAO-56 Penman-Monteith potential evapotranspiration (ET_o) calculated from data provided by a nearby standard weather station belonging to the Agroclimatic Information Network of the Junta de Andalusia. Precipitation (*P*) collected in the orchard, and irrigation amounts (IA) supplied to the trees of each treatment. Values in % next to the IA values correspond to the percentage of the irrigation needs (% IN) actually supplied by irrigation. See text for details on the treatments. All data are in millimeters. AVG = average. DOY = day of year.

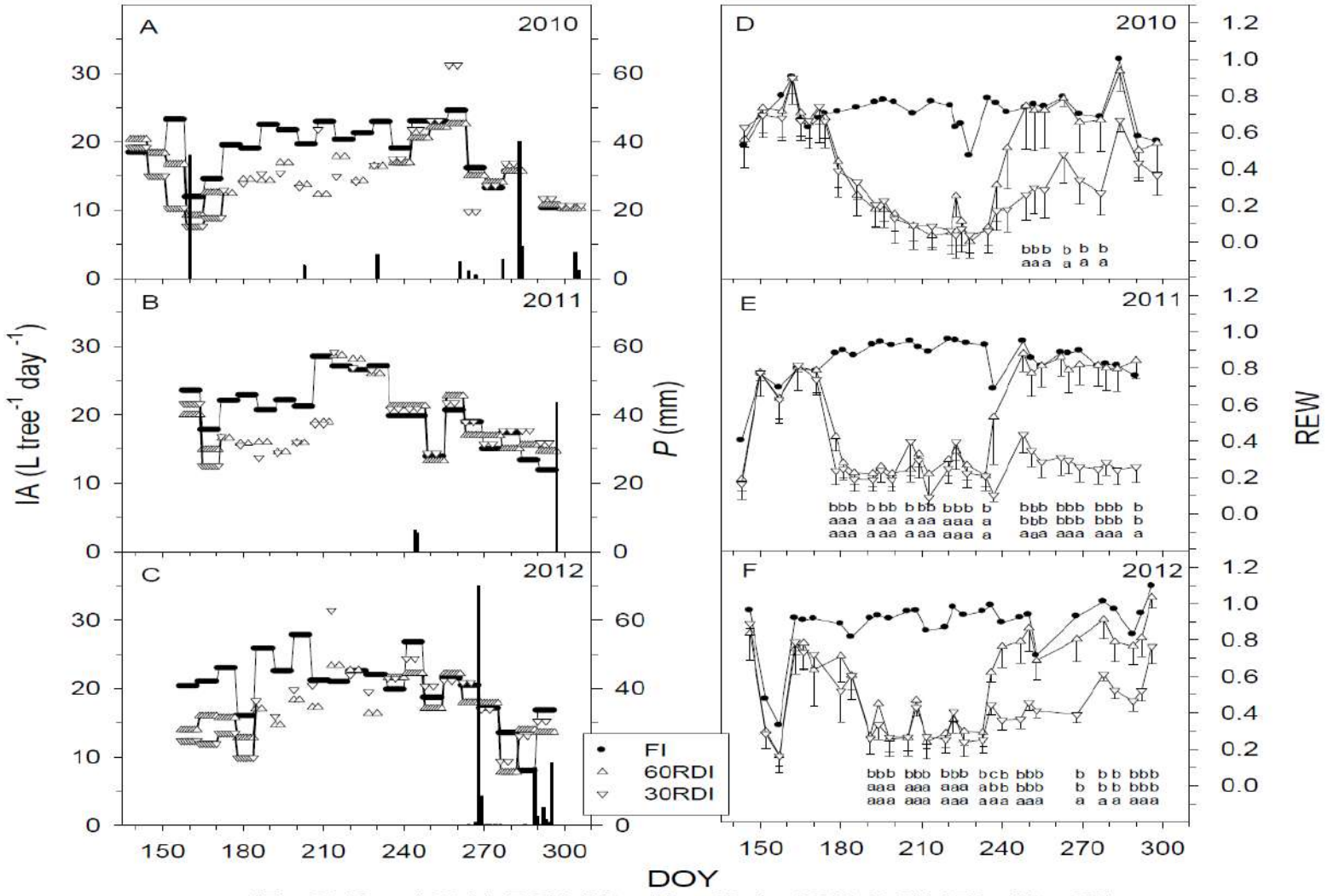
	2010		2011		2012	
	Whole year	**Irrigation period (DOY 138-306)**	**Whole year**	**Irrigation period (DOY 158-297)**	**Whole year**	**Irrigation period (DOY 157-296)**
ET_o	1466.5	997.5	1473.6	796.4	1598.2	914.8
P	912.0	119.0	477.0	55.0	404.6	86.0
IA in FI		502.0 (101 % IN)		477.2 (107 % IN)		478.7 (102 % IN)
IA in 60RDI		308.0 (62 % IN)		288.3 (65 % IN)		291.3 (63 % IN)
IA in 30RDI		148.0 (30 % IN)		127.3 (29 % IN)		134.6 (29 % IN)

3-year average

- ET_c: 731 mm
- IA in FI: 4860 m^3 ha^{-1}
- IA in 60RDI: 2959 " (61 %)
- IA in 30RDI: 1366 " (28 %)

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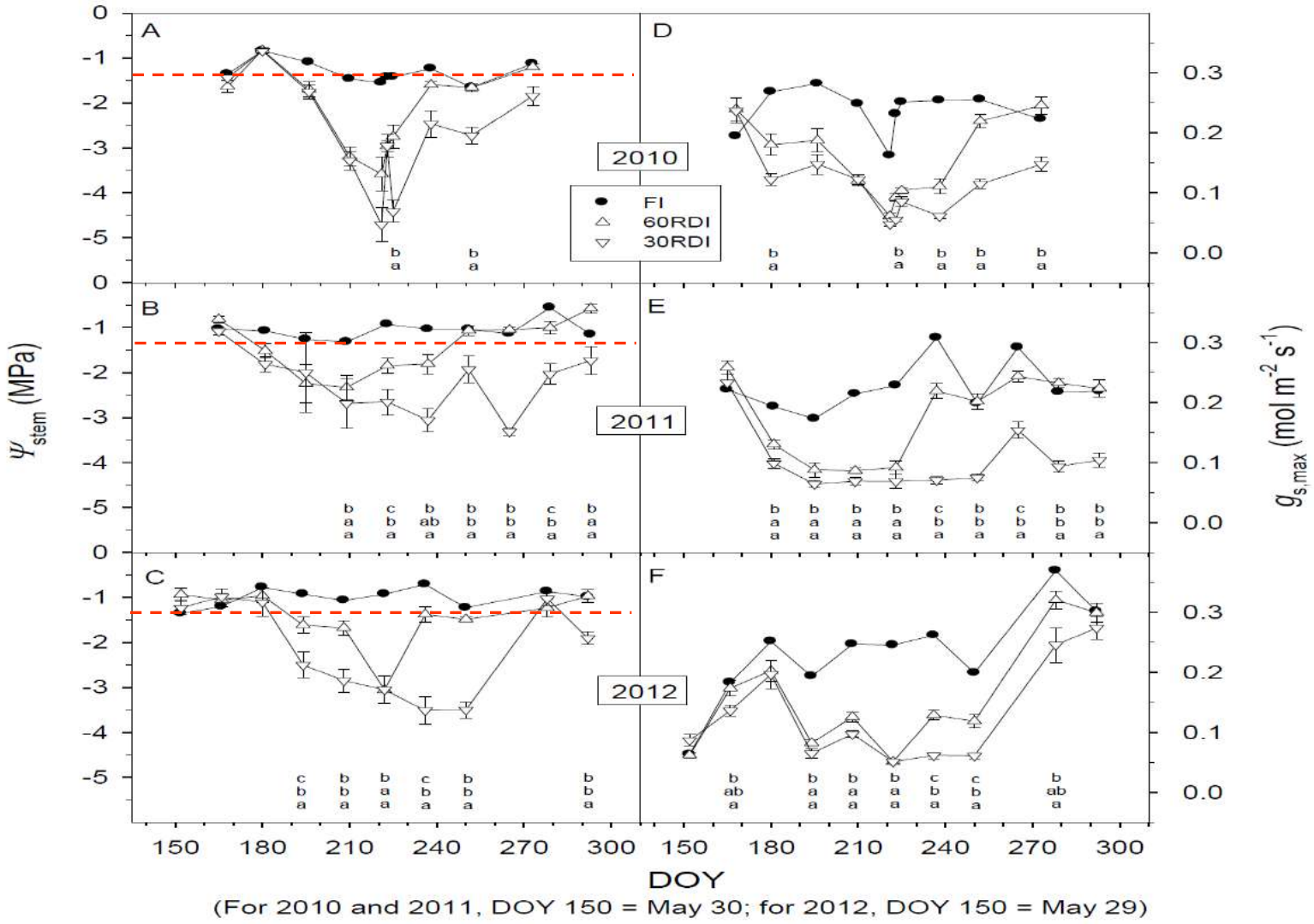
RDI in a SHD olive orchard with decreasing IAs



(For 2010 and 2011, DOY 150 = May 30; for 2012, DOY 150 = May 29)

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RDI in a SHD olive orchard with decreasing IAs

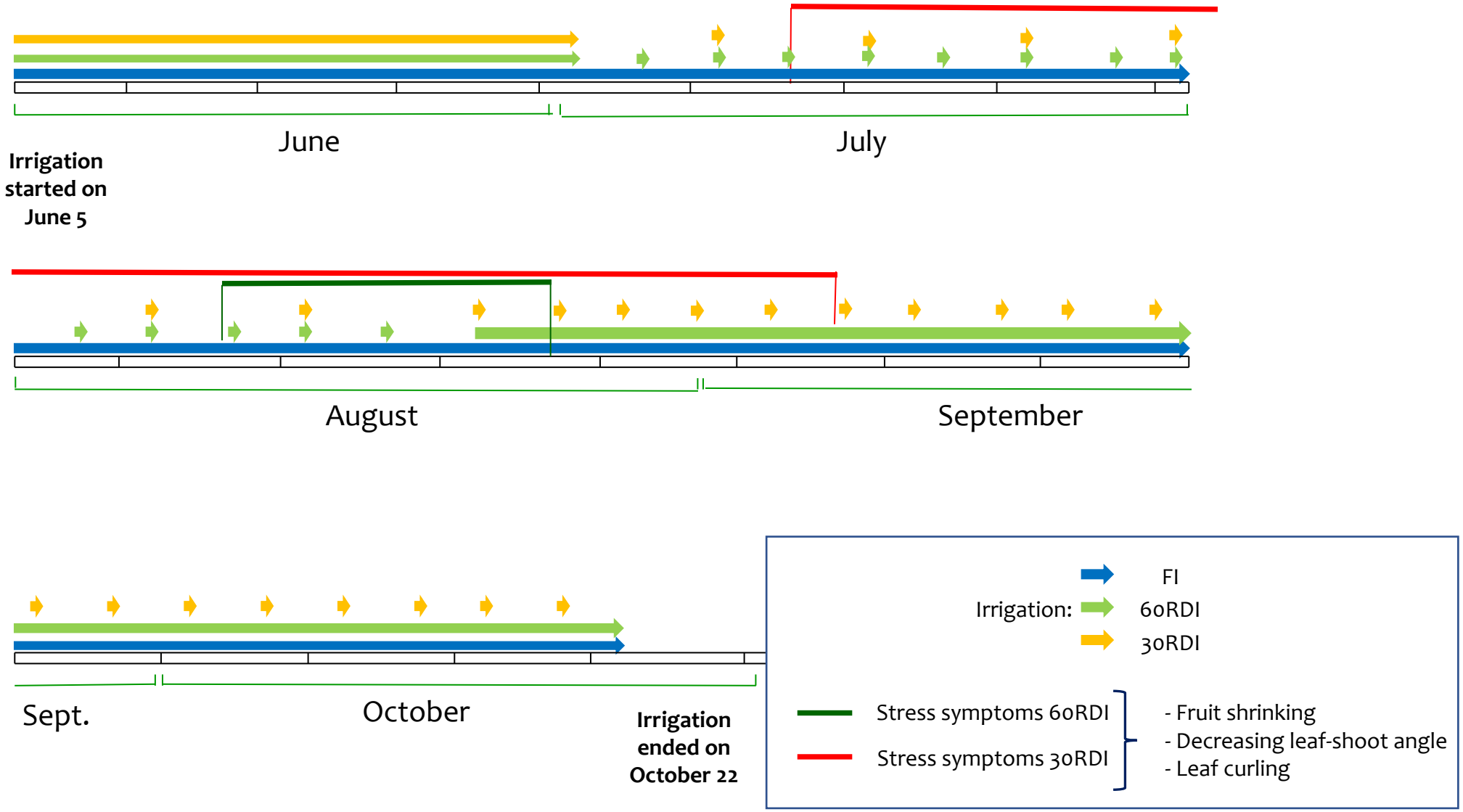


(For 2010 and 2011, DOY 150 = May 30; for 2012, DOY 150 = May 29)

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Do not irrigate based on visual symptoms!

2012



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RDI in a SHD olive orchard with decreasing IAs

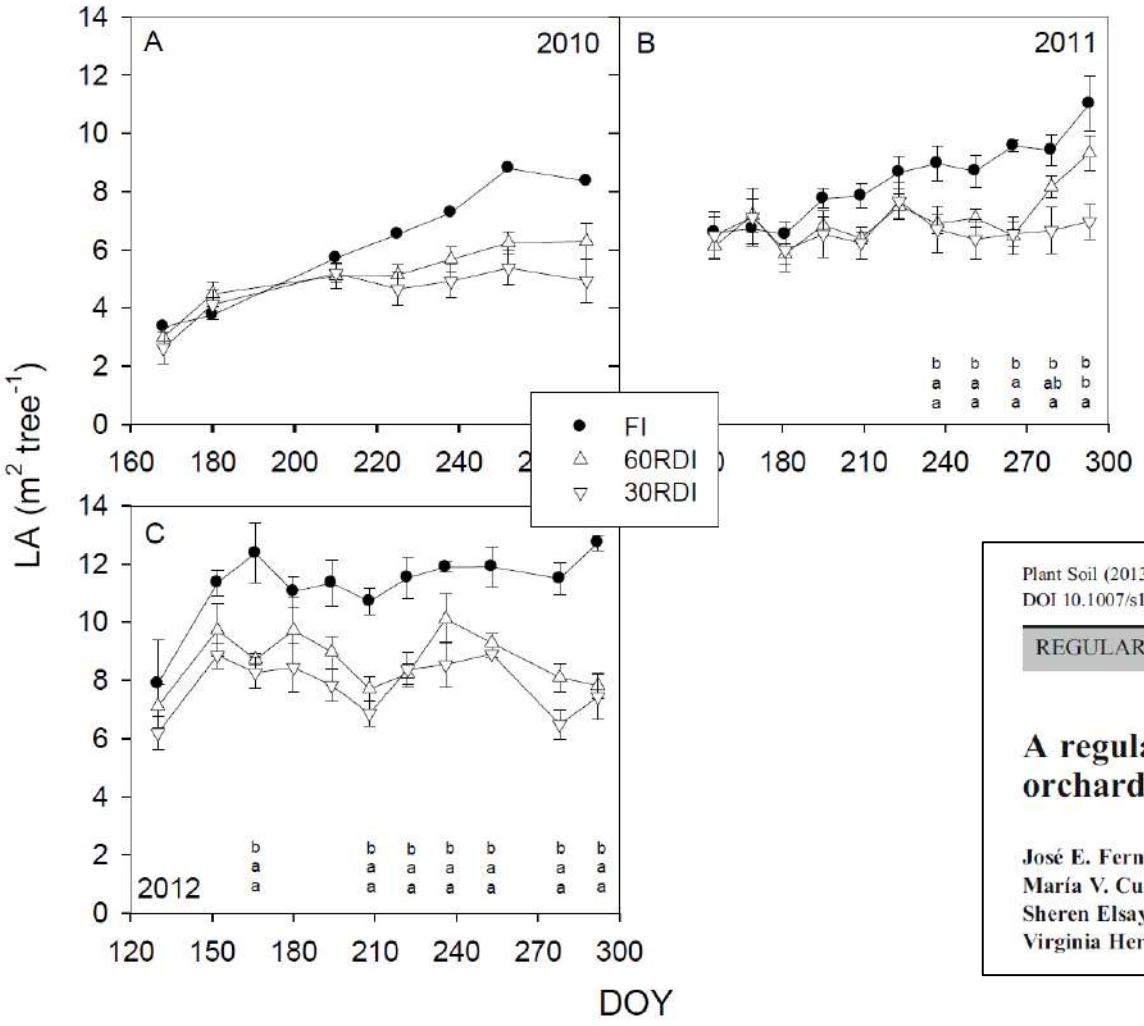
Table 4. Fruit and virgin olive oil (VOO) yields, and pulp/stone ratio for each year and treatment. Values between brackets refer to the VOO yield expressed as percentage of the fresh fruits weight. Different letters indicate significant differences between treatments at $p < 0.05$. Values of the FI treatment in 2010 were not considered in the statistical analyses, because of the lack of replications.

Year	Treatment	Fruit yield (kg ha^{-1})	VOO yield (kg ha^{-1})	Pulp/stone ratio
2010	FI	15606.9	998.4 (6.4%)	3.3
	60RDI	12678.6 b	913.3 (7.2%) a	3.2 b
	30RDI	9183.5 a	867.3 (9.4%) a	2.3 a
2011	FI	19760.8 c	1270.0 (6.4%) b	3.5 c
	60RDI	14477.4 b	860.4 (5.8%) a	2.9 b
	30RDI	9729.4 a	931.4 (9.8%) a	2.4 a
2012	FI	23612.1 b	1291.6 (5.4%) b	4.2 b
	60RDI	18275.8 a	740.2 (4.0%) a	4.0 b
	30RDI	16227.0 a	828.3 (5.1%) a	3.0 a

Treatment	IA (m^3 ha^{-1})	Fruit yield (kg ha^{-1})	Oil yield (kg ha^{-1})
FI	4,860	19,660	1,187
60RDI	2,959 (61 %)	15,144 (77 %)	834 (70 %)
30RDI	1,366 (28 %)	11,713 (60 %)	875 (74 %)

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RDI in a SHD olive orchard with decreasing IAs



(For 2010 and 2011, DOY 150 = May 30; for 2012, DOY 150 = May 29)

Plant Soil (2013) 372:279–295
DOI 10.1007/s11104-013-1704-2

REGULAR ARTICLE

A regulated deficit irrigation strategy for hedgerow olive orchards with high plant density

José E. Fernández · Alfonso Perez-Martin · José M. Torres-Ruiz · María V. Cuevas · Celia M. Rodriguez-Dominguez · Sheren Elsayed-Farag · Ana Morales-Sillero · José M. García · Virginia Hernandez-Santana · Antonio Diaz-Espejo

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RDI in a SHD olive orchard with decreasing IAs

CHAPTER 9

Precision Irrigation in Olive (*Olea europaea* L.) Tree Orchards

José E. Fernández[1], Antonio Diaz-Espejo[1], Rafael Romero[1], Virginia Hernandez-Santana[1], José M. García[2], Carmen M. Padilla-Díaz[1], María V. Cuevas[1]
[1]Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC), Seville, Spain;
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Water Scarcity and Sustainable Agriculture in Semiarid Environment
ISBN 978-0-12-813164-0
https://doi.org/10.1016/B978-0-12-813164-0.00009-0

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Table 9.2 Irrigation amounts (IA) supplied to the trees of each irrigation treatment tested at the hedgerow olive orchard at the Sanabria farm over 6 years of the experiment described in Section 6.1

	Irrigation amount (mm)					
Year	FI	60RDI	45RDI	30RDI	ET_o (mm)	*P* (mm)
2010	502.0 (101%)	308.0 (62%)		148.0 (30%)	1466.5	912.0
2011	477.2 (107%)	288.3 (65%)		127.3 (29%)	1473.6	477.0
2012	478.7 (102%)	291.3 (63%)		134.6 (29%)	1598.2	404.6
2013	367.6 (85%)[a]		197.9 (46%)		1464.3	476.4
2014	462.9 (92%)		238.2 (47%)		1437.6	549.4
2015	585.5 (101%)		287.0 (50%)		1581.3	237.6
AVG ± SE	479.0 ± 28.6	295.9 ± 6.1	241.0 ± 25.8	136.6 ± 6.1	1503.6 ± 27.8	509.5 ± 91.4

AVG ± SE, average ± standard error; ET_o, yearly value of the FAO-56 Penman–Monteith potential evapotranspiration calculated from data provided by a nearby standard weather station; *FI*, full irrigation; *P*, yearly precipitation collected in the orchard. Values in parentheses refer to the IA expressed as a percentage of the irrigation needs for full irrigation, calculated for each treatment with the crop coefficient approach; *RDI*, regulated deficit irrigation.
[a]In 2013 the irrigation season started about 3 weeks later than required, because of problems with the irrigation system.

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RDI in a SHD olive orchard with decreasing IAs

Table 9.3 Fruit yields recorded for each irrigation treatment tested at the hedgerow olive orchard at the Sanabria farm over 6 years of the experiment described in Section 6.1

	Fruit yield (kg ha^{-1})			
Year	FI	60RDI	45RDI	30RDI
2010	15609.8	12680.9 (81%)		9185.2 (59%)
2011	19764.4	14480.0 (73%)		9731.1 (49%)
2012	23616.4	18140.3 (77%)		16229.9 (69%)
2013	22559.8		14952.1 (66%)	
2014	19283.0		16036.5 (83%)	
2015	19724.8		15073.8 (76%)	
AVG ± SE	20093.0 ± 1147.4	15100.4 ± 1606.2	15354.1 ± 343.0	11715.4 ± 2262.7

AVG ± SE, average ± standard error; *FI*, full irrigation; *RDI*, regulated deficit irrigation. Values in parentheses refer to the fruit yield expressed as a percentage of the FI fruit yield. See Fernández et al. (2013) for details of the sampling procedure.

Table 9.4 Oil yields recorded for each irrigation treatment tested at the hedgerow olive orchard at the Sanabria farm over 6 years of the experiment described in Section 6.1

	Oil yield (kg ha^{-1})			
Year	FI	60RDI	45RDI	30RDI
2010	999.0	912.1 (91%)		865.4 (86%)
2011	1264.8	861.2 (68%)		932.2 (74%)
2012	1291.2	733.3 (57%)		816.5 (63%)
2013	1557.1		867.6 (56%)	
2014	1875.8		1416.9 (76%)	
2015	1957.4		1387.4 (71%)	
AVG ± SE	1490.9 ± 153.1	835.5 ± 53.2	1224.0 ± 178.4	871.4 ± 33.5

AVG ± SE, average ± standard error; *FI*, full irrigation; *RDI*, regulated deficit irrigation. Values in parentheses refer to the oil yield expressed as a percentage of the FI oil yield. See Fernández et al. (2013) for details of the sampling and oil extraction procedures.

The 45RDI treatment led to fruit and oil yields equal to 80 % and 74 % of those in FI.

The trees were pruned every year, in December-January, to 4-6 m² LA. The average LA in the 45RDI trees at the end of the growing season was ca. 75 % of that in the FI trees.

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RDI in a SHD olive orchard with decreasing IAs

Table 9.5 Water productivity (WP) values in terms of fresh fruit and olive oil for each irrigation treatment tested at the hedgerow olive orchard at the Sanabria farm over 6 years of the experiment described in Section 6.1

	WP for fruit (kg fruit m^{-3} water supplied by irrigation)				WP for oil (kg oil m^{-3} water supplied by irrigation)			
Year	FI	60RDI	45RDI	30RDI	FI	60RDI	45RDI	30RDI
2010	3.11	4.12		6.21	0.20	0.30		0.58
2011	4.14	5.02		7.64	0.27	0.30		0.73
2012	4.93	6.23		12.05	0.27	0.25		0.61
2013	6.14		7.55		0.42		0.44	
2014	4.16		6.73		0.41		0.59	
2015	3.37		5.25		0.33		0.48	
AVG ± SE	4.31 ± 0.45	5.12 ± 0.61	6.51 ± 0.67	8.63 ± 1.76	0.32 ± 0.04	0.28 ± 0.02	0.50 ± 0.04	0.64 ± 0.05

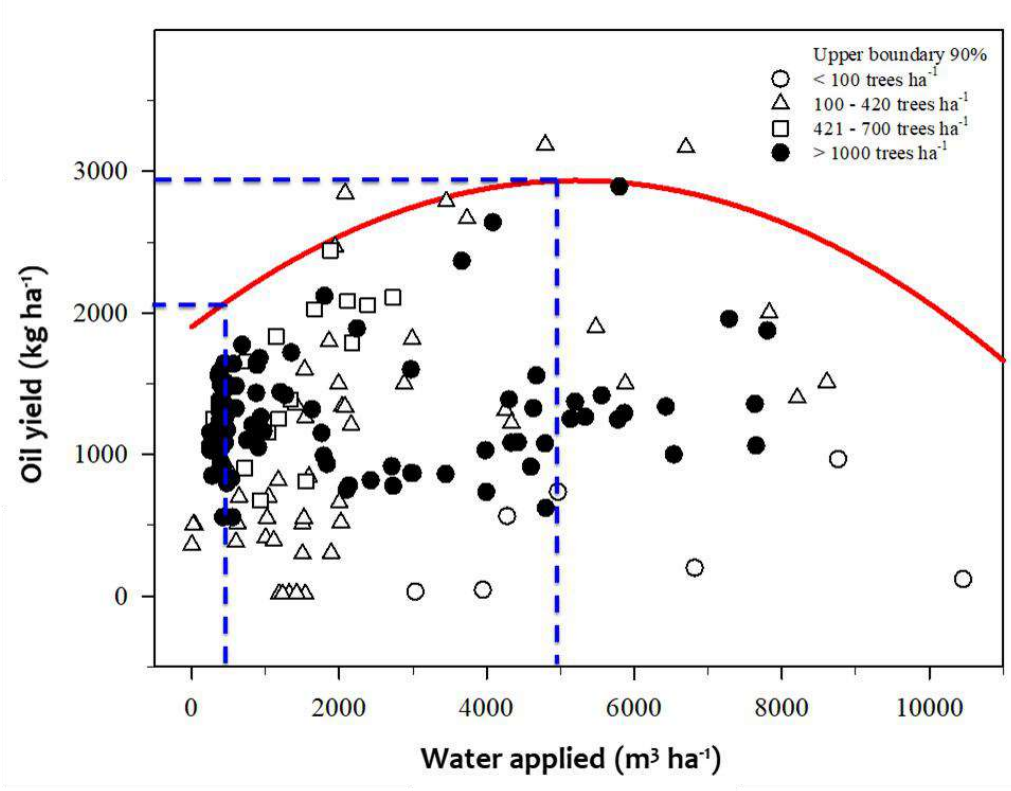
AVG ± SE, average ± standard error; *FI*, full irrigation; *RDI*, regulated deficit irrigation.

The WP values can be compared among treatments, because they have been obtained from treatments applied simultaneously and in the same orchard.

But the WP values say little about the efficiency of irrigation. As expected, WP values were 30RDI > 45RDI > FI.

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RDI in a SHD olive orchard with decreasing IAs



$$WP_c = \frac{yield}{TWU}$$

$$WP_c = \frac{3000}{5000} = 0{,}6 \ kg\ m^{-3}$$

$$WP_c = \frac{2000}{500} = 4 \ kg\ m^{-3}$$

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RDI in a SHD olive orchard with decreasing IAs

Agricultural Water Management 245 (2021) 106577

Contents lists available at ScienceDirect

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Evaluation of regulated deficit irrigation strategies for oil olives: A case study for two modern Israeli cultivars

Alon Ben-Gal [a,*], Yonatan Ron [a], Uri Yermiyahu [b], Isaac Zipori [c], Sireen Naoum [d], Arnon Dag [c]

"Results showed a general trend of increased water productivity as a function of reduced irrigation but since yields tended to be reduced when irrigation was decreased, there was not a clear benefit of RDI over sustained deficit irrigation"

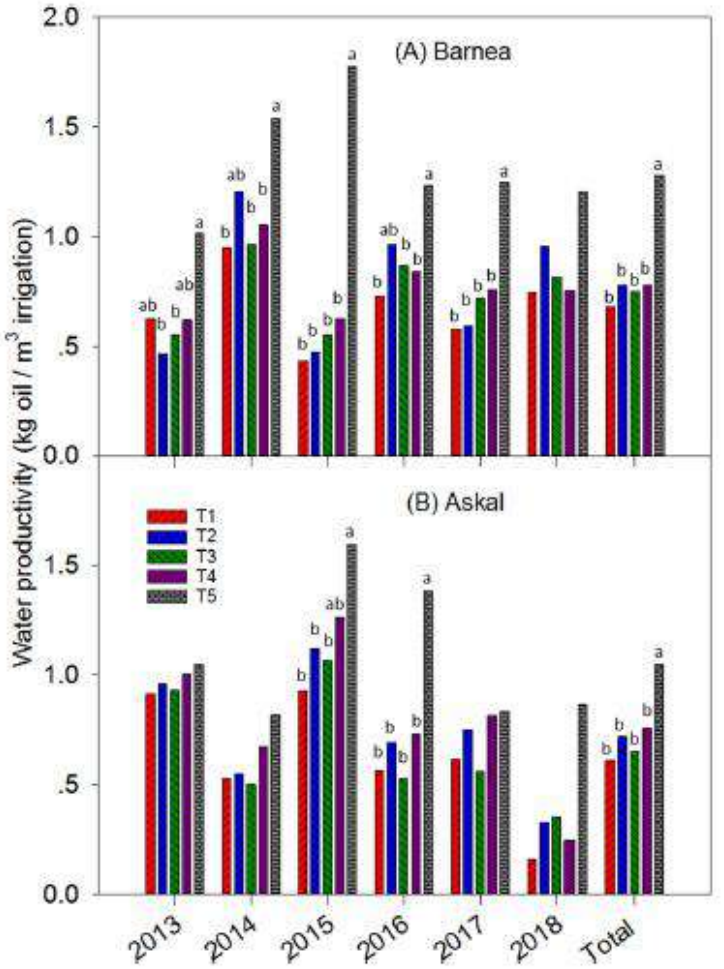


Fig. 10. Water productivity (kg oil per cubic meter of irrigation water) per season and accumulate total for the experiment per treatment. (A) Barnea, (B) Askal. Different letters indicate significant differences between treatments in each year.

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And what about quality?

'Arbequina I-18' trees, in California







2002 treatments: 15 %, 25 %, 40 %, 57 %, 71 %, 89 %, 107 % of ET_c
2003 " : 28 %, 33 %, 55 %, 74 %, 93 %, 117 %, 140 % of ET_c

Berenguer et al. (2006) — Greater production: irrigation with 75 % ET_c
Grattan et al. (2006) — Better Quality: irrigation with 35 % ET_c

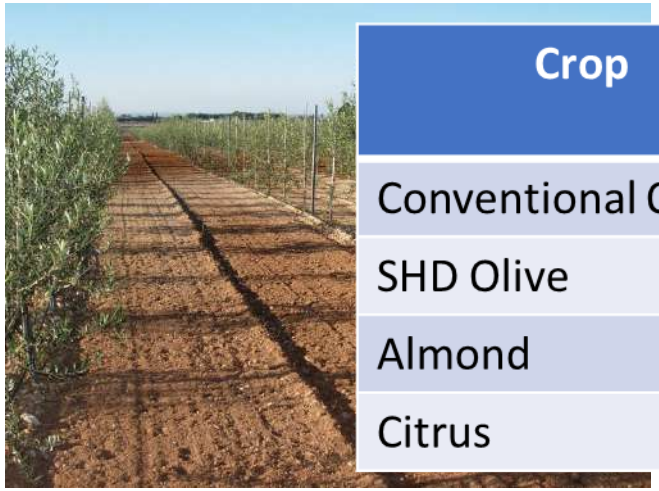
Berenguer, M.J., Vossen, P.M., Grattan, S.R., Connell, J.H., Polito, V.S., 2006. Tree irrigation levels for optimum chemical and sensory properties of olive oil. Horticultural Science 41, 427-432.

Grattan, S.R., Berenguer, M.J., Connell, J.H., Polito, V.S., Vossen, P.M., 2006. Olive oil production as influenced by different quantities of applied water. Agricultural Water Management 85, 133-140.

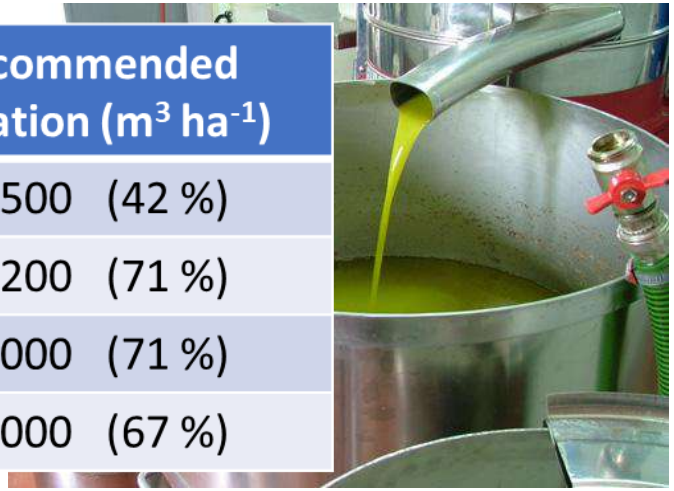
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And what about quality?

'Arbequina I-18' trees, in California



Crop	Full irrigation (m^3 ha^{-1})	Recommended Irrigation (m^3 ha^{-1})
Conventional Olive	3500	1500 (42 %)
SHD Olive	4500	3200 (71 %)
Almond	7000	5000 (71 %)
Citrus	6000	4000 (67 %)



2002 treatments: 15 %, 25 %, 40 %, 57 %, 71 %, 89 %, 107 % of ET_c
2003 " : 28 %, 33 %, 55 %, 74 %, 93 %, 117 %, 140 % of ET_c

Berenguer et al. (2006) — Greater production: irrigation with 75 % ET_c
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And what about quality?

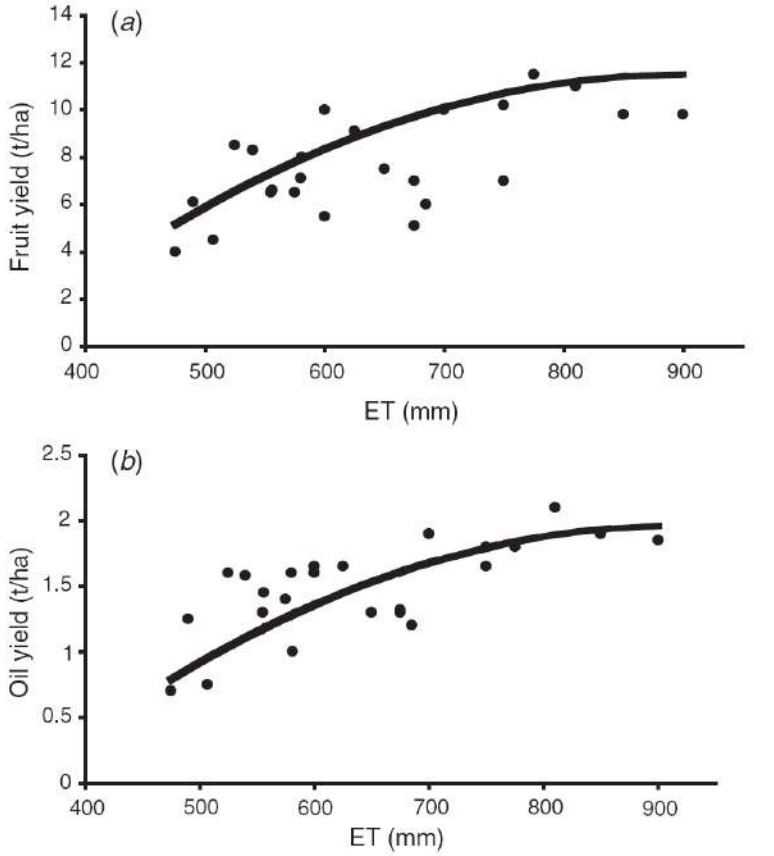


Fig. 1. Relationship of (*a*) fruit (t/ha) and (*b*) oil yield (t/ha) to evapotranspiration for an 18-year-old 'Picual' orchard submitted to various irrigation strategies at Córdoba, Spain. Adapted from Moriana *et al.* (2003).

1. Irrigation increased both the number of fruits and their size and, terefore, irrigation increased production

2. Unlike other fruit tree species, in olive the production functions were not linear

3. Irrigation, however, decreased both the percentage of olive oil in the fruit and the extractability

4. The effect of irrigation on both the fatty accid composition and the acidity was negligible.

5. The phenolic compounds, which improve estability and organoleptic characterisitcs, decreased with irrigation

6. The colour, aroma, and other organoleptic characteristics were negatively affected by irrigation.

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And what about quality?



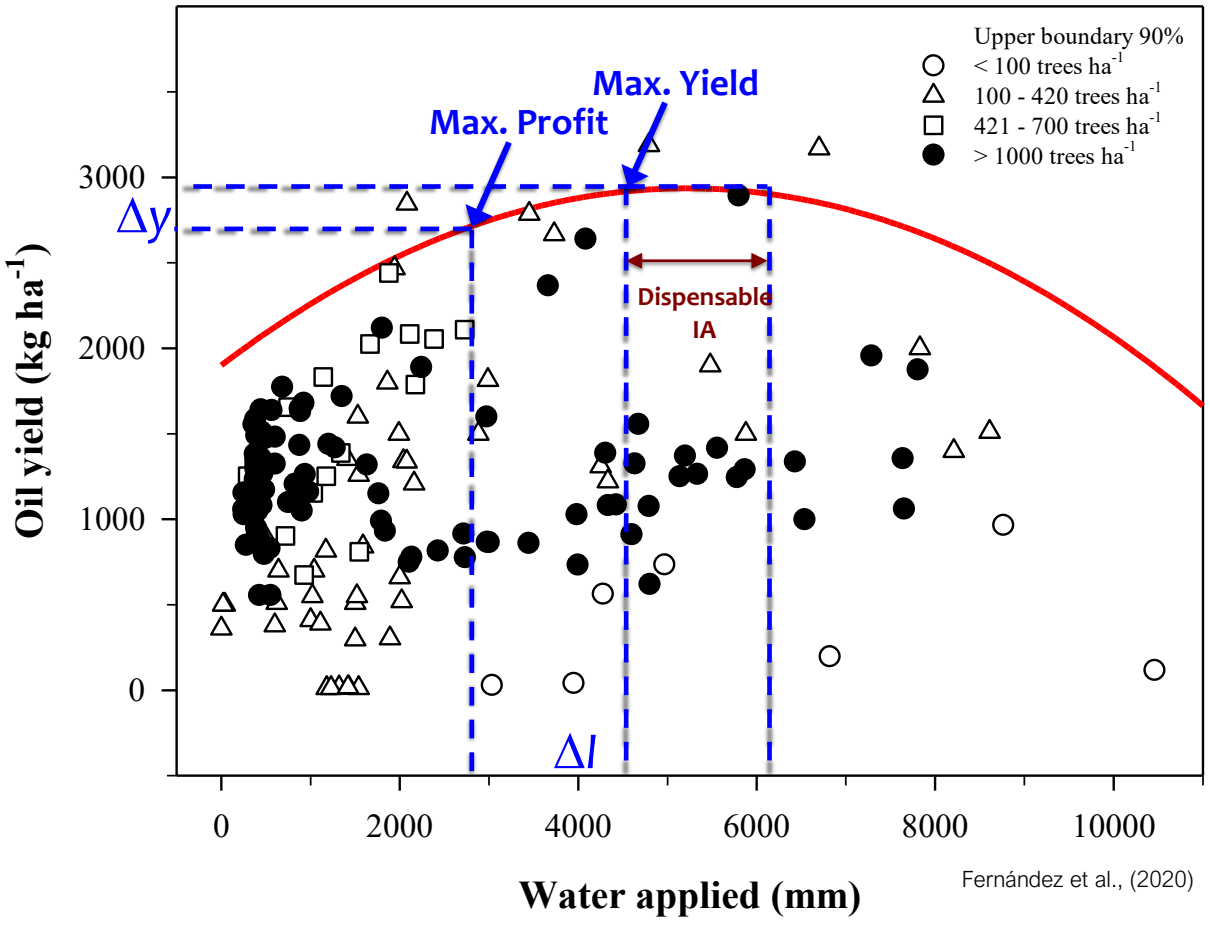
In summary, deficit irigation increased quality and decreased yield.

Watch out! A single rain event before harvesting may lead to similar quality than in FI

And, is the grower going to be paid for quality?

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Socio-economic aspects



Fernández et al., (2020)

Maximum EWP_c is achieved by irrigating until null marginal benefit:

To remain below the threshold for the cost of applying ΔI being greater than the market value of Δy.

Barker et al. (2003)

When the price of the product depends on quality, deficit irrigation may be appealing to growers.

If don't, maximum EWP_c is achieved for irrigation amounts close to those required for maximum yield.

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Irrigation Scheduling



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Plant Ecophysiology and Irrigation group
Spanish National Research Council (CSIC)

Irrigation scheduling

1. The context

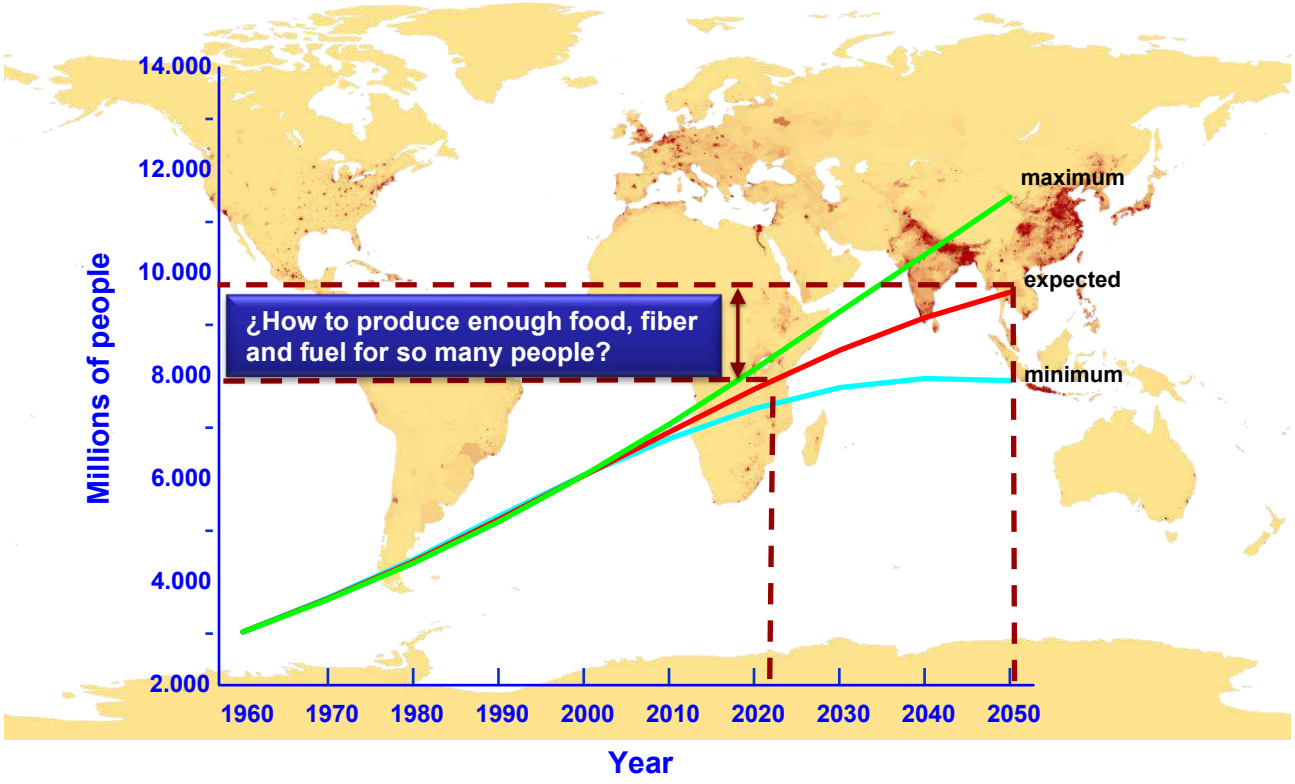
2. Methods to schedule irrigation

3. Scheduling irrigation in practice

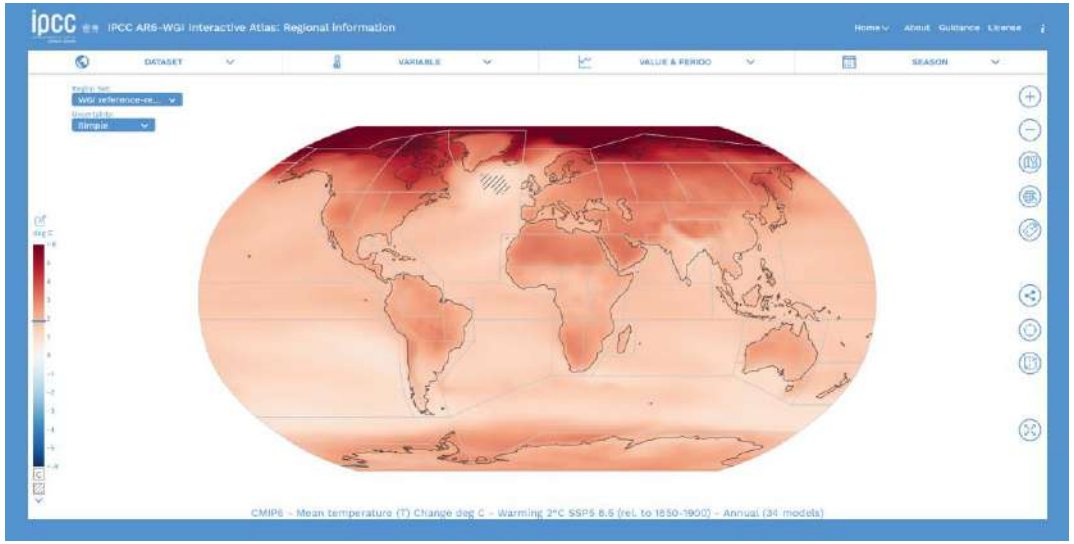
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The challenges of irrigation scheduling

Increasing global population



Climatic threat



The global land ET increased by 10±2 % between 2003 and 2019, and it will further increase in a warming climate (Pascolini-Cambell, 2021)

We will have to produce more food with less water

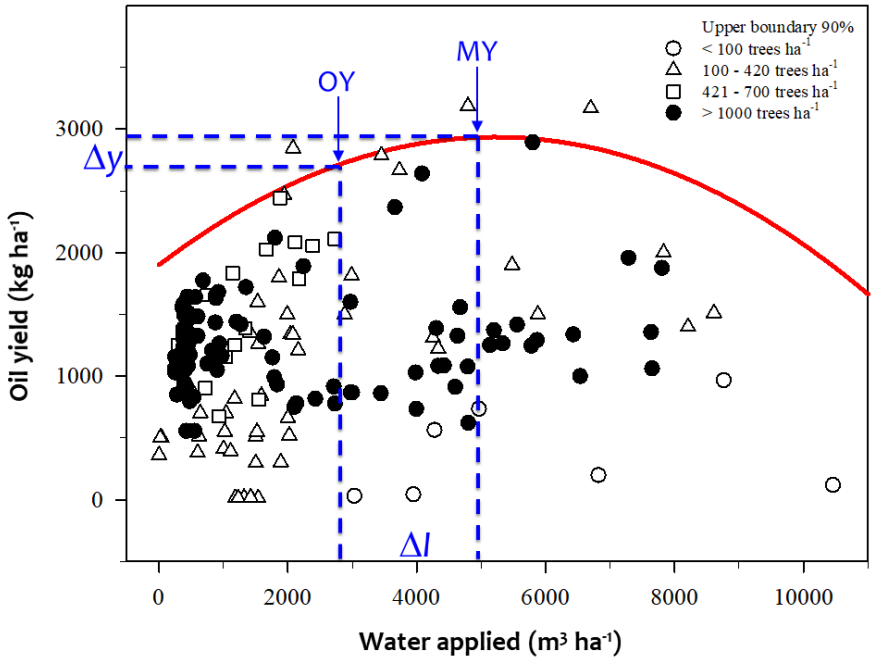
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The challenges of irrigation scheduling

Irrigation scheduling (IS) consists on determining the timing and amount of each irrigation event, all along the irrigation season of a crop, to achieve the production target.

- The IS approach must be cheap and easy to use (?)

- The IS approach must be suitable for deficit irrigation strategies



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The challenges of irrigation scheduling

- The IS approach must be precise: both the lack of water and new management systems demand it.





The more complicated a system is, the more rigorous and precise its management must be

- It must be suitable for precision irrigation (PI).

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The challenges of irrigation scheduling



Precision irrigation consists on appling the right amount of water to each plant and with the right timing.

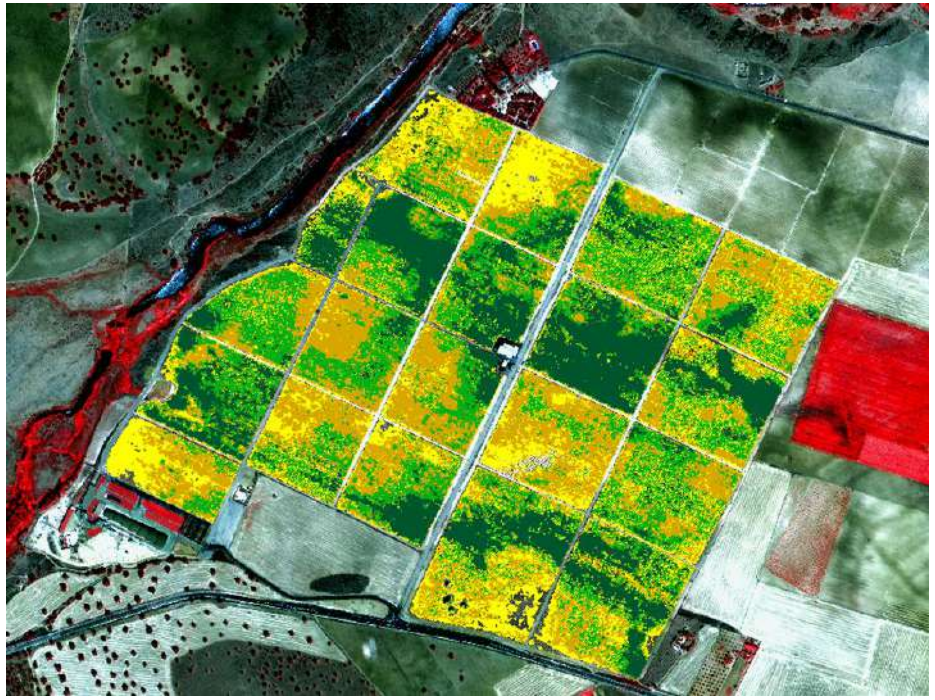
To do so, we must identify the variability within the farm/orchard:

- No crop: with soil maps
- Crop: with remote imagery

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The challenges of irrigation scheduling

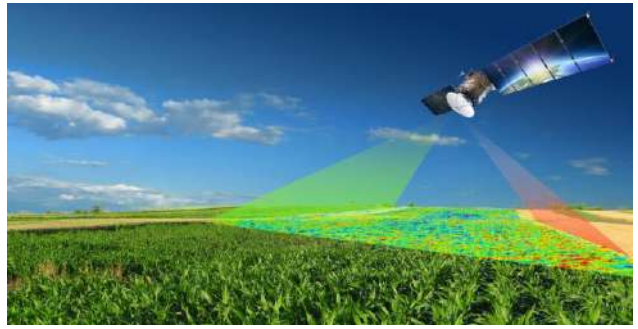
The Normalized Difference Vegetation Index (the **canopy NDVI index),** highly related to tree vigour, is determined from remote imagery.











The canopy NDVI index: Cell structures reflect the different light waves in visible and near-infrared bands, depending on the “health” of the crop.

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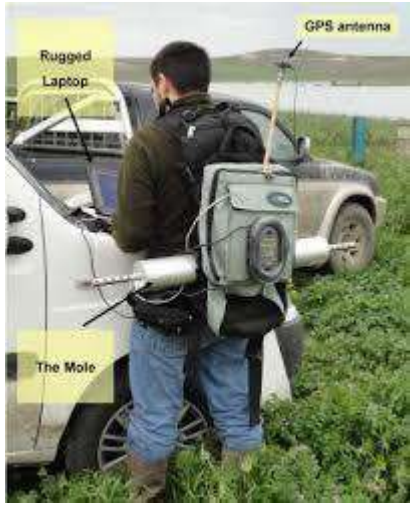
Proximal soil sensors to determine soil spatial variability



The EM38-Mk2 electromagnetic induction sensor (Geonics Ltd., Canada).
It measures the apparent electrical conductivity (EC_a) at 0-075 m and 0-1.5 m depths.
The outputs depend on soil texture, stoiness, bulk density and soil moisture, among other soil characteristics.

The Dualem-1S sensor (Dualem, Canda) measures EC_a at 0-0.50 m and 0-1.5 m depths.





The Mole gamma-ray spectroradiometer (Soil Company, The Netherlands) measures the natural gamma-ray emisión coming from the first 0.3-0.4 m of the soil. It is used to survey topsil features, including textura, gravel content, potassium and organic carbon.

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Proximal soil sensors to determine soil spatial variability

Appl. Sci. **2022**, *12*, 1309. https://doi.org/10.3390/app12031309

applied sciences

MDPI

Article

Remote and Proximal Sensing Techniques for Site-Specific Irrigation Management in the Olive Orchard

Giovanni Caruso [1], Giacomo Palai [1,*], Riccardo Gucci [1] and Simone Priori [2]

Sensors **2020**, *20*, 2526; doi:10.3390/s20092526

sensors

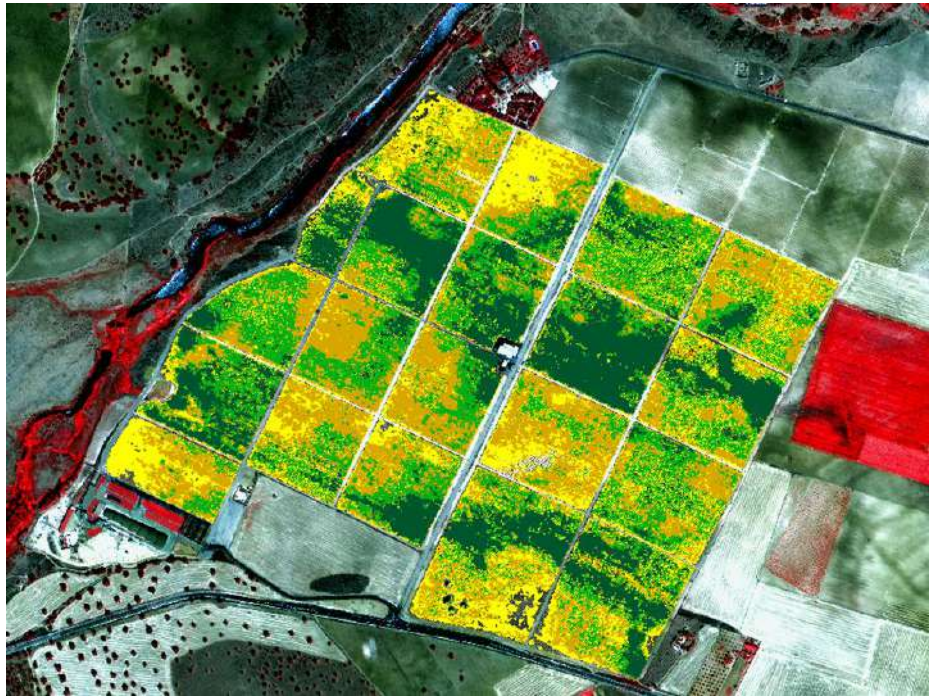
MDPI

Article

Automatic Irrigation Scheduling on a Hedgerow Olive Orchard Using an Algorithm of Water Balance Readjusted with Soil Moisture Sensors

Sandra Millán [1,*], Carlos Campillo [1], Jaume Casadesús [2], Juan Manuel Pérez-Rodríguez [1] and Maria Henar Prieto [1]

The challenges of irrigation scheduling



Precision irrigation consists on appling the right amount of water to each plant and with the right timing.

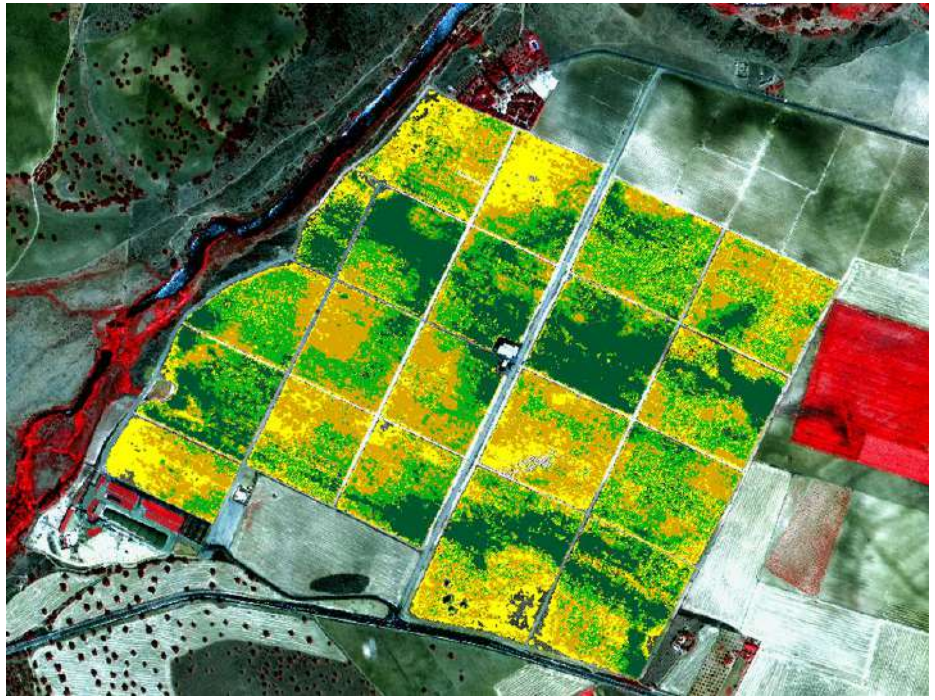
To do so, we must identify the variability within the farm/orchard:

- No crop: with soil maps
- Crop: with remote imagery

Zonation or zonification: we define agronomic management units in large, highly variable commercial farms/orchards.

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The challenges of irrigation scheduling



Identifying agronomic management units (AMUs) allows us:

- To irrigate the AMUS of each kind differently from others.

  (Try to define the AMUs from the start, based on soil analyses)

- To select a reduced but representative number of sites for irrigation scheduling monitoring

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The challenges of irrigation scheduling



Identifying the AMUs is useful not only to irrigate 'à la carte', but also to reduce the cost of monitoring the orhcard.

How to instrument a large and highly variable farm/orchard?

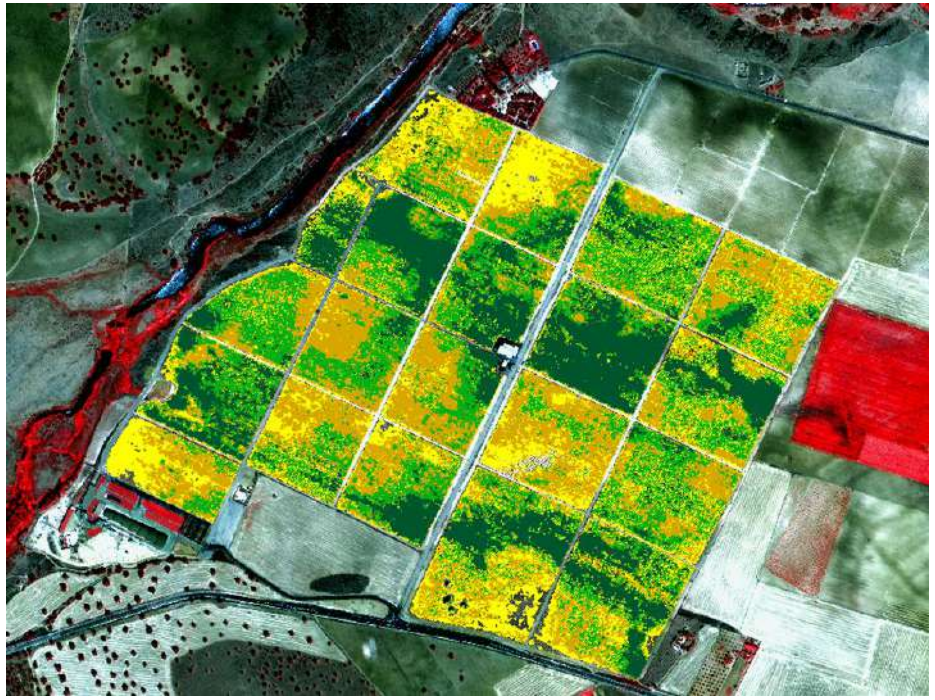
How many sites should I instrument?

Where?

How representative will my measurements be?

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The challenges of irrigation scheduling



Identifying the AMUs is useful not only to irrigate 'à la carte', but also to reduce the cost of monitoring the orhcard.

How to instrument a large and highly variable farm/orchard?

How many sites should I instrument?

Where?

How representative will my measurements be?

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The challenges of irrigation scheduling

- The IS approach must be precise: both the lack of water and new management systems demand it.





The more complicated a system is, the more rigorous and precise its management must be.

- It must be suitable for precision irrigation (PI)

- It must be digital: decisions must be taken from data, and not only from the intuition or experience of the irrigator.

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The challenges of irrigation scheduling





The digitalization of irrigation consists on the use of sensors, remote imagery, simulation models, advanced data processing methods (AI) and other digital approaches to manage irrigation : Agriculture 4.0, 5.0…

The current tendency is to digitalize agriculture (subsides from the EU).

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Irrigation scheduling

1. The context

2. Methods to schedule irrigation

3. Scheduling irrigation in practice

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Irrigation can be scheduled from…



… weather measurements



… plant-based measurements







… soil water measurements





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Irrigation can be scheduled from…



… weather measurements



… plant-based measurements







There is not "the best method":

- The suitability of a particular approach or method depends on many factors (investment capacity, training of the irrigator, orchard/farm characteristics…)
- Each method has advantages and disadvantages.

The point is to choose the method that best fits your conditions.

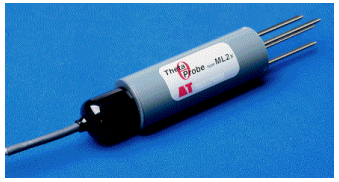




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IS from soil water measurements



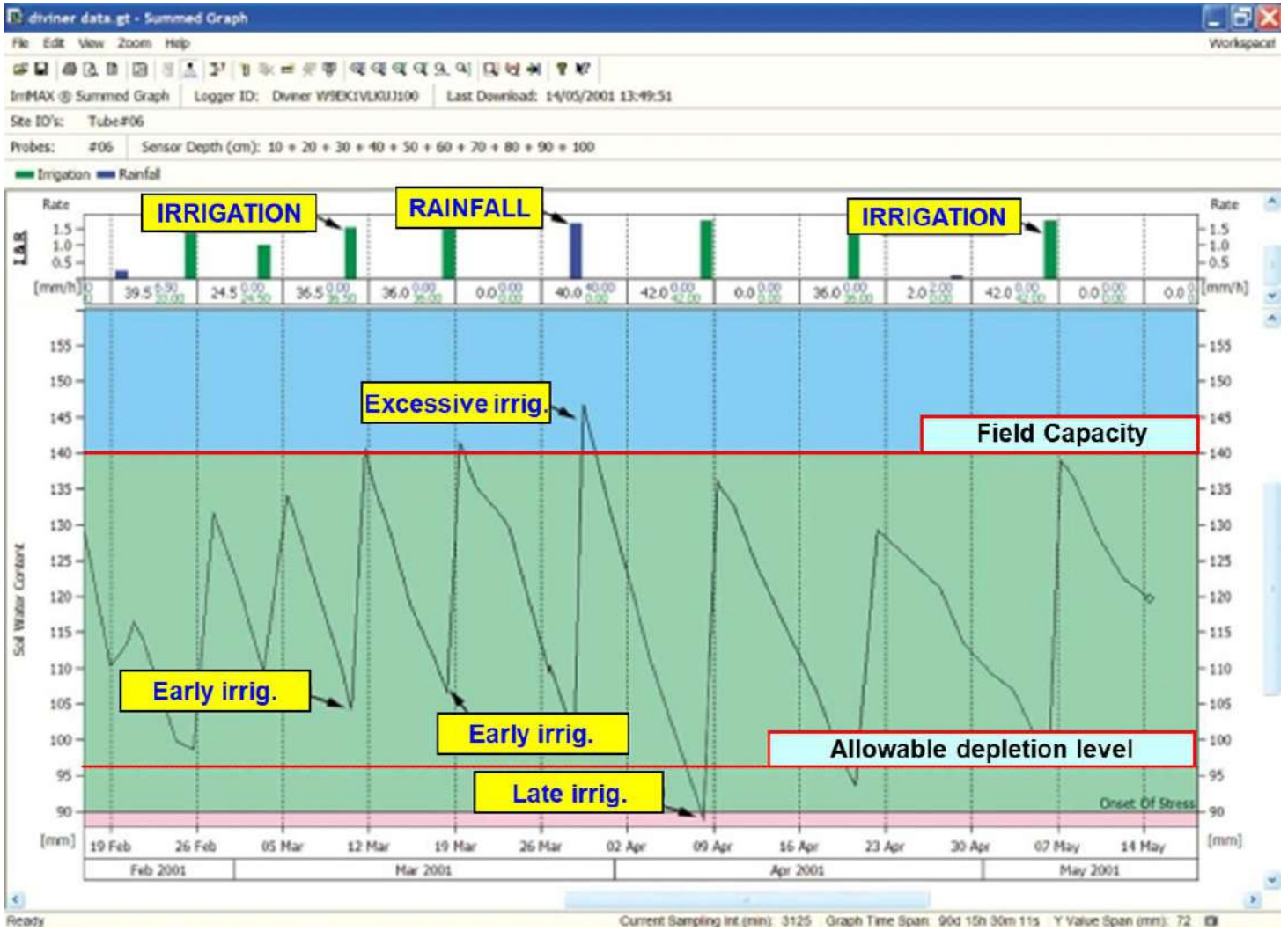






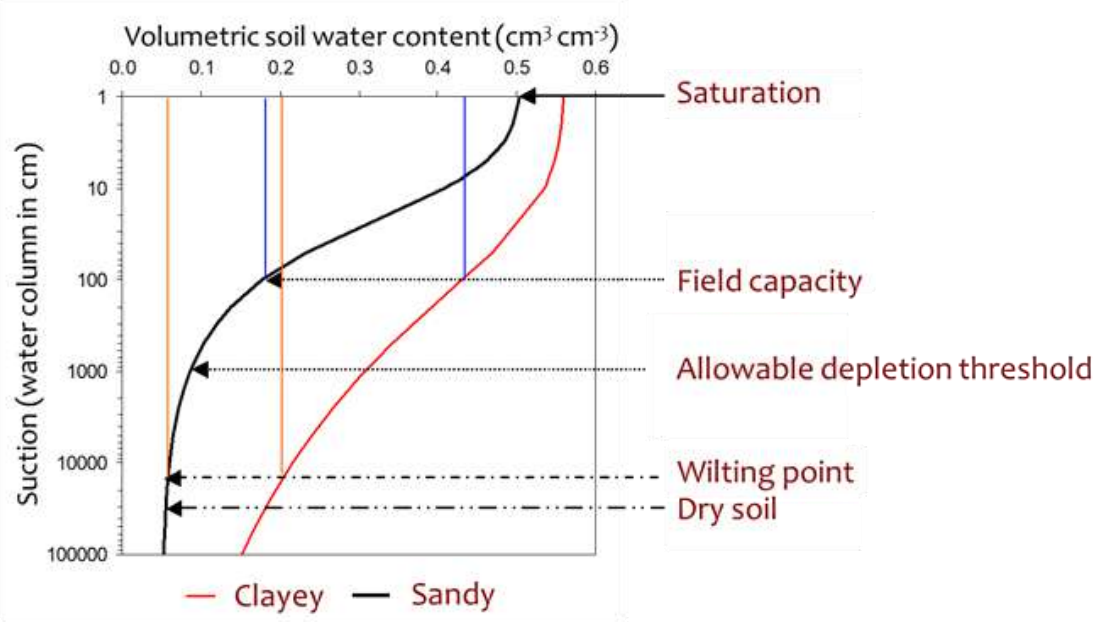




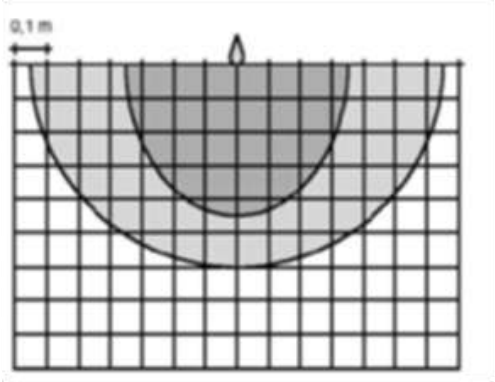


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IS from soil water measurements

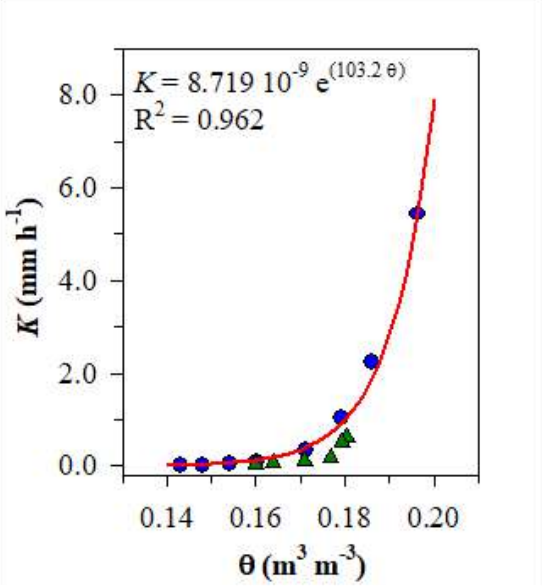


The water retention curve



Water stored in the soil

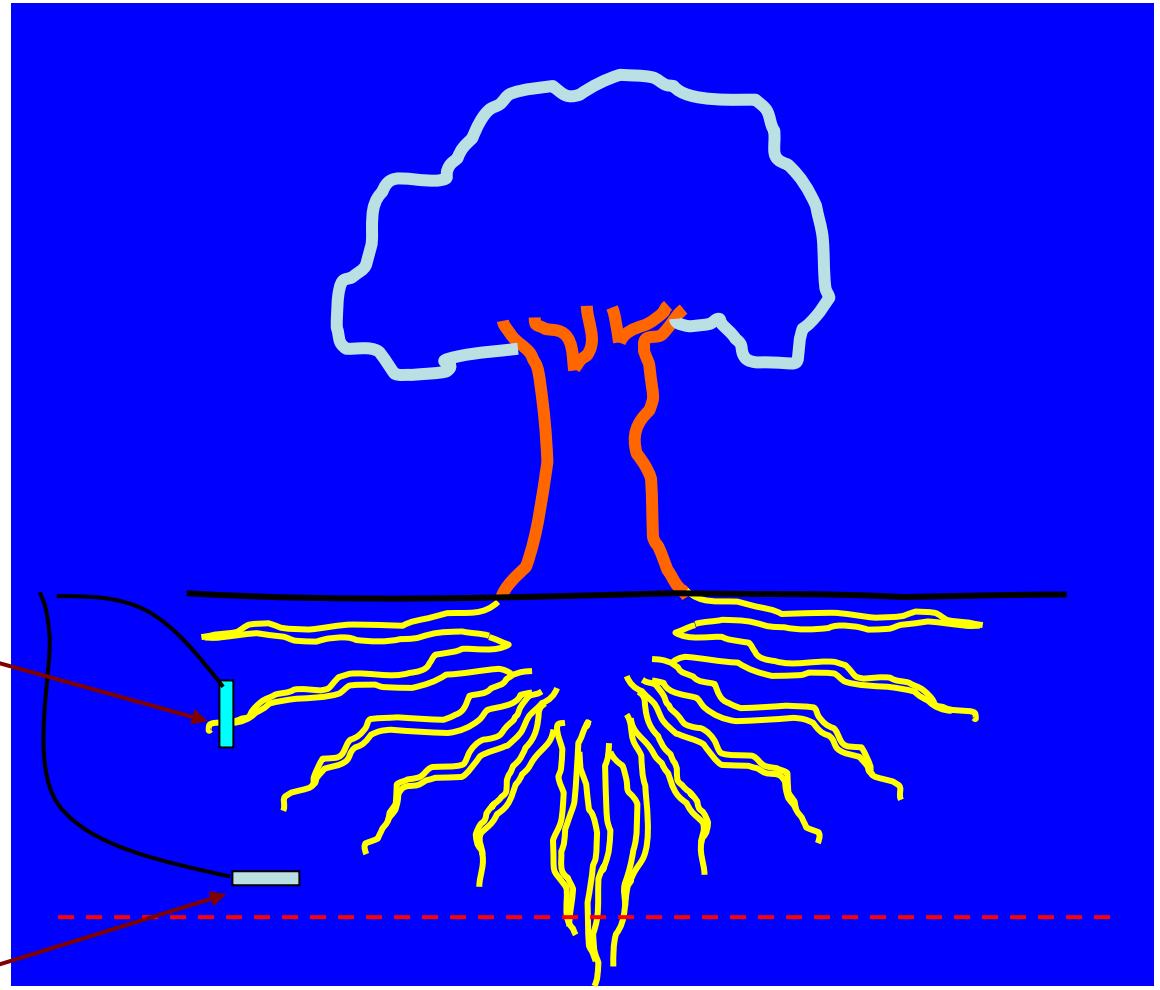
The volume of the root zone



The soil hydraulic conductivity

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What to do if you do not know *K*?



Good quality ϑ_v sensor at the depth of maxium root density

Cheap ϑ_v sensor at some 15-20 cm above the effective rooting depth

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Soil water measurements in commercial farms/orchards

For relatively wet soils only
(from 0 to - 0.8 bar = - 80 kPa = - 0.08 MPa)





Gypsum, nylon or fiberglass blocks
(from – 0.03 to – 0.8 MPa)





Watermark and other Electronic tensiometers
(from – 0.05 to - 1,5 MPa)

Most widely used sensors are capacitive sensors, based on the FDR principle. For details:

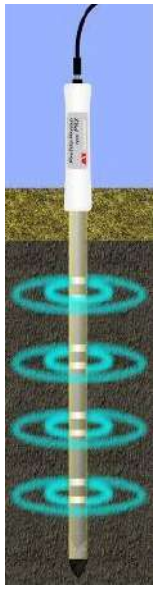
J.E. Fernández et al. (2000) Water Uptake. *In*: Root Methods. A Handbook, Chapter 14th. A.L. Smit et al. (Eds.) Springer. ISBN 3-540-66728-8

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Soil water measurements in commercial farms/orchards



TDR devices measure the velocity of propagation of a high-frequency signal in the soil in between the two rods of the sensor. This velocity depends on the amount of water in the soil.





FDR devices measure the soil capacitance and conductivity, both depending on water content, at a fixed frequency.

FDR devices are less expensive and nearly as accurate as TDR devices: they are more widely used.

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Soil water measurements in commercial farms/orchards

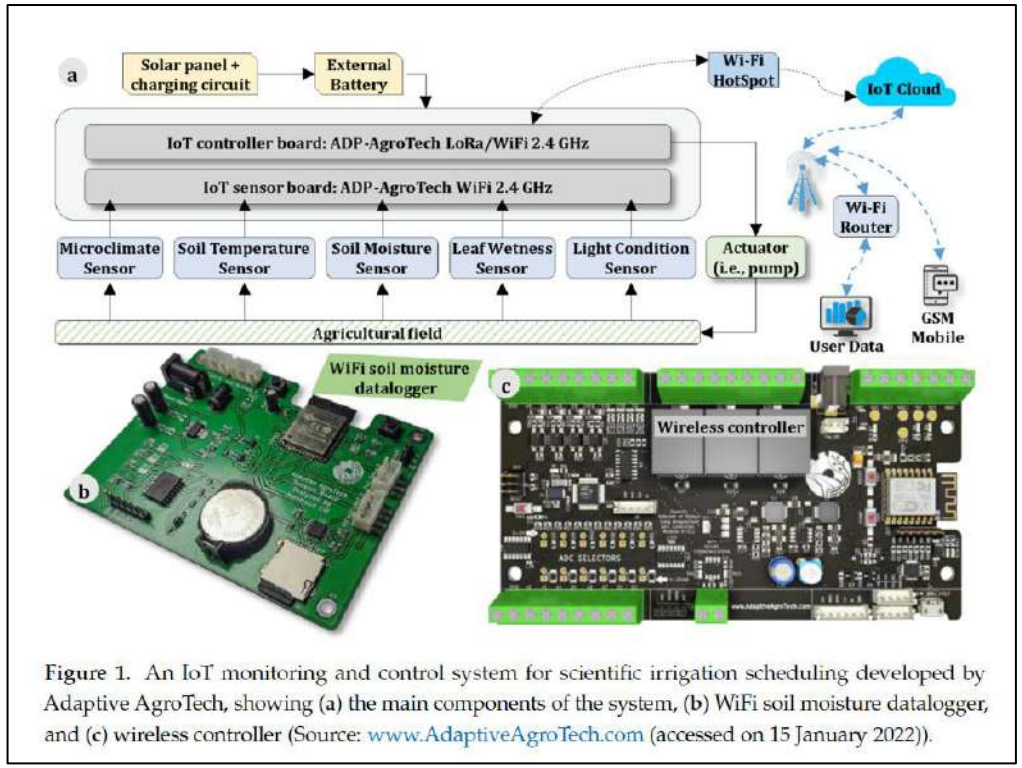


Figure 1. An IoT monitoring and control system for scientific irrigation scheduling developed by Adaptive AgroTech, showing (a) the main components of the system, (b) WiFi soil moisture datalogger, and (c) wireless controller (Source: www.AdaptiveAgroTech.com (accessed on 15 January 2022)).

Agriculture 2022, *12*, 564. https://doi.org/10.3390/agriculture12040564

agriculture

MDPI

Article

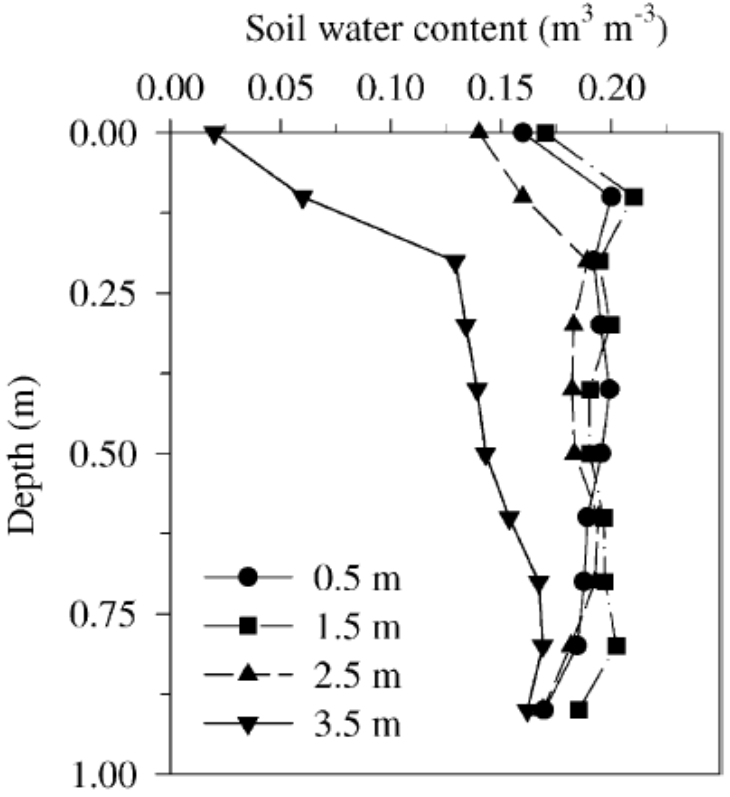
Scientific Irrigation Scheduling for Sustainable Production in Olive Groves

Marjan Aziz [1,*], Madeeha Khan [1], Naveeda Anjum [1], Muhammad Sultan [2], Redmond R. Shamshiri [3,*], Sobhy M. Ibrahim [4], Siva K. Balasundram [5] and Muhammad Aleem [2]

Sensors can be interfaced with Internet of Things (IoT) sensing and control systems, to improve data collection, automation, and remote control of irrigation.

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Processing the soil water measurements



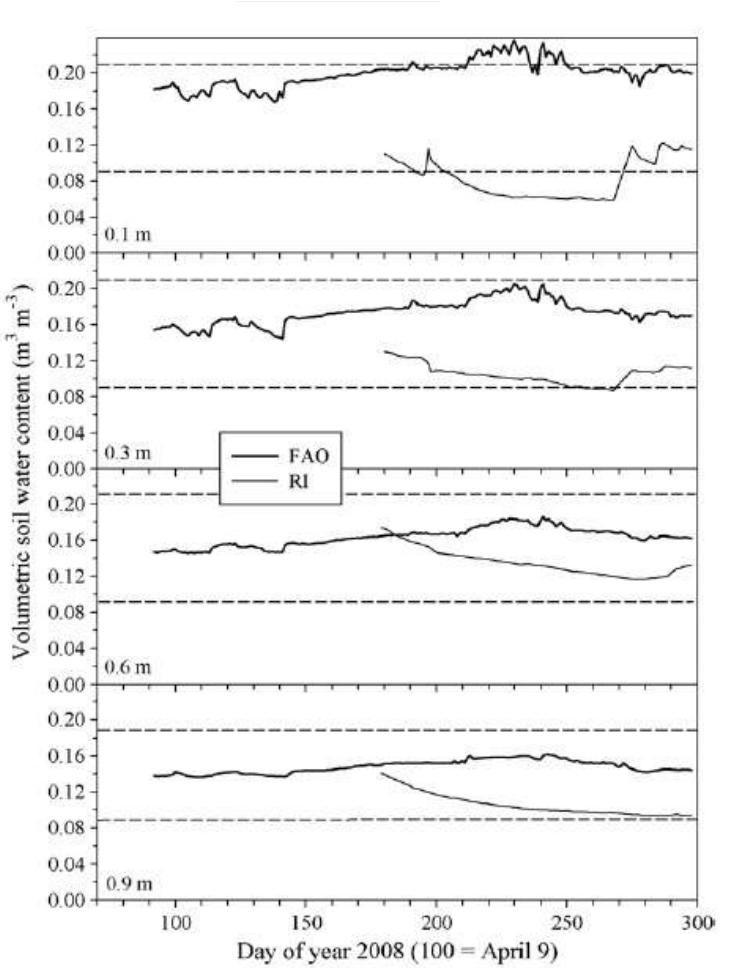


Fig. 2. Time course of the volumetric soil water contents (θ_v) recorded at different depths by the Verdtech stations installed in the FAO and RI plots. The dotted lines indicate the θ_v values for soil matric potential values of −0.03 MPa (field capacity) and −1.5 MPa (wilting point).

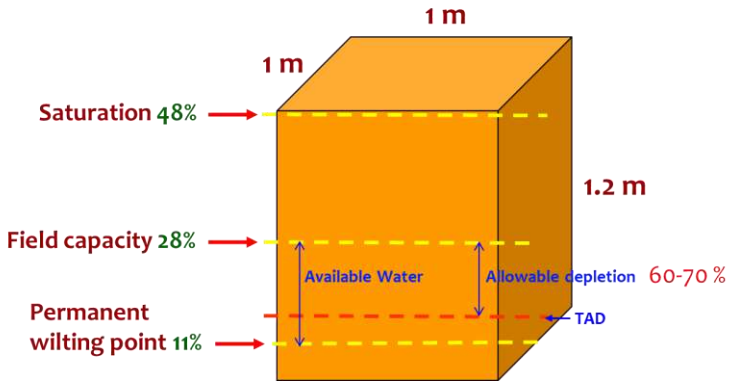
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Processing the soil water measurements

The Relative Extractable Water (REW) in the root zone

$$REW = (R - R_{min}) / (R_{max} - R_{min})$$

R (mm) = actual soil water content
R_{min} (mm) = minimum soil water content measured in a period when the soil becomes dry
R_{max} (mm) = soil water content at field capacity



SOURCE: J.E. Fernández et al. (2013). A regulated deficit irrigation strategy for hedgerow olive orchards with high plant density. Plant and Soil 372, 279-295

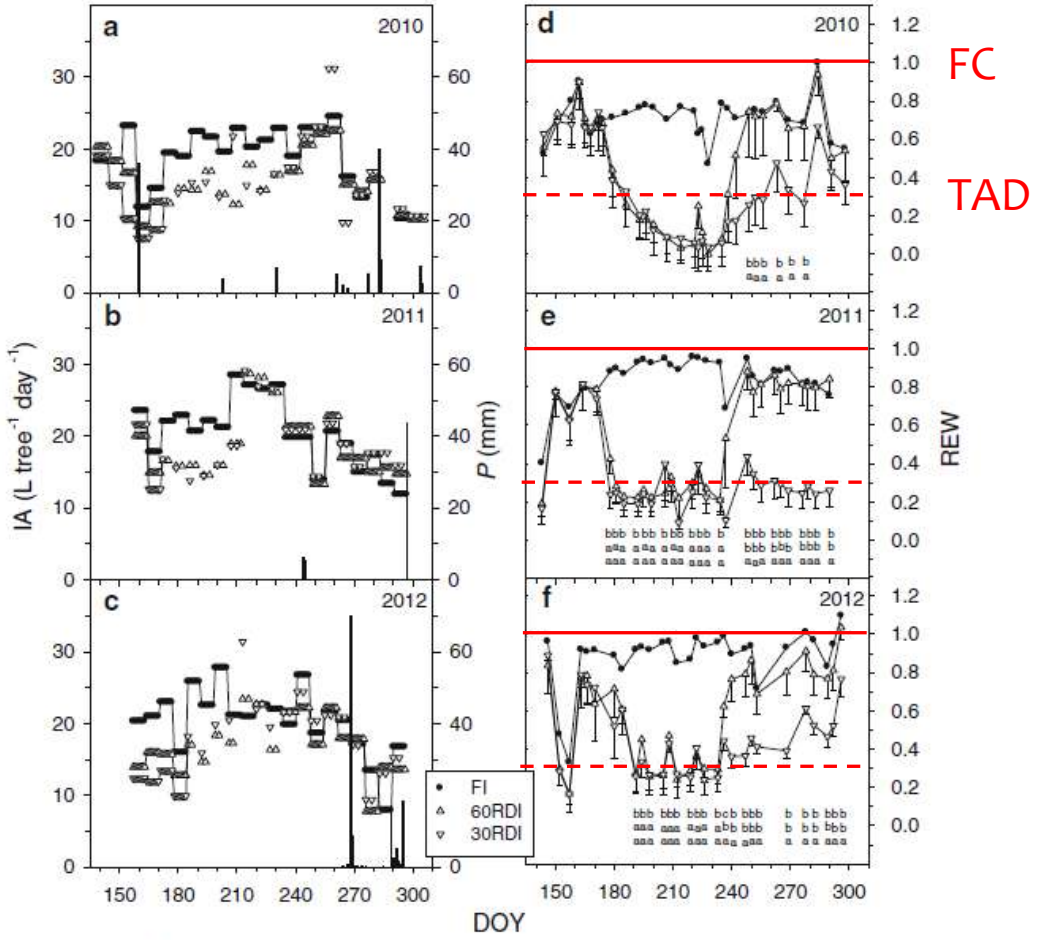


Fig. 3 Seasonal courses both of the irrigation amount (IA) supplied to the each treatment and precipitation (P) collected in the orchard (a,b,c). The seasonal courses of the relative extractable water (REW) derived from the soil water contents measured in the plots of each treatment are also shown (d,e,f). Different *letters* indicate significant differences between treatments, at $p<0.05$. *Letters* are not shown when no differences were found. REW values for the FI treatment in 2010 were not considered in the statistical analysis because they correspond to one plot only. DOY = day of year (For 2010 and 2011, DOY 150 = May 30; for 2012, DOY 150 = May 29)

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Calculating REW from the soil water measurements

The amount of water in the soil (mm) is calculated by multiplying the measured volumetric soil water content ($m^3\ m^{-3}$) by the soil volume (m^3) corresponding to that measurement





$$REW = (R - R_{min}) / (R_{max} - R_{min})$$

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IS from soil water measurements













PROS:

- Cheap (?)
- Easy to install and maintain
- It can be used by growers

CONS:

- High variability
- Relationships between soil water depletion and crop performance are not always known
- Neither the atmospheric demand nor the physiology of the plant are considered

IS from meteorological measurements



The crop coefficient approach (Doorenbos and Pruitt, 1977):

$$ET_c = K_c\, ET_o$$

$$K_c = K_s K_{cb} + K_e \qquad \text{(Allen et al., 1998)}$$

$$K_c = K_p + K_{pd} + K_{s1}\,(1\text{-}F_w) + K_{s2}\,(F_w) \qquad \text{(Orgaz et al., 2006)}$$

Agricultural Water Management, Special Issue **Updating FAO56 Methods**

L. Pereira, D. Hunsaker, R. López-Urrea, P. Paredes, N. Jovanovic (Eds.)

July 2021

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IS from meteorological measurements



The Allen&Pereira approach (Allen and Pereira, 2009):

It uses field observations of the ground fraction covered by the crop (f_c) and tree height (h), as well as a parameter that characterizes the canopy opacity (M_L) and another one that characterizes the effect of stomatal adjustment on tree transpiration (F_r)

This approach is less empirical than the CC approach.

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IS from meteorological measurements

The Allen&Pereira approach:

				Tree height					observed average value	
Month	**Kc A&P**	**Kcb A&P**	**Measured fc**	**(m)**	**ML**	**Fr**	**Kd**	**Kcbfull**	**Rhmin (%)**	**u (m/s)**
Jan	0,37	0,37	0,39	2,70	1,50	0,50	0,59	0,60	44,12	2,26
Feb	0,39	0,39	0,39	2,70	1,50	0,50	0,59	0,63	39,54	2,80
Mar	0,40	0,40	0,39	2,70	1,50	0,51	0,59	0,64	37,90	3,09
Apr	0,39	0,39	0,39	2,70	1,50	0,50	0,59	0,64	35,31	2,76
May	0,44	0,44	0,42	2,96	1,50	0,51	0,63	0,67	24,63	2,95
Jun	0,44	0,44	0,42	2,93	1,50	0,51	0,63	0,67	24,11	3,11
Jul	0,47	0,47	0,45	3,11	1,50	0,51	0,67	0,67	23,35	3,08
Aug	0,48	0,48	0,47	3,15	1,50	0,50	0,70	0,67	20,40	2,75
Sep	0,49	0,49	0,49	3,27	1,50	0,50	0,73	0,65	26,83	2,43
Oct	0,38	0,38	0,39	2,70	1,50	0,49	0,59	0,61	29,42	1,70
Nov	0,37	0,37	0,39	2,70	1,50	0,49	0,59	0,59	40,74	1,73
Dec	0,35	0,35	0,39	2,70	1,50	0,48	0,59	0,57	43,15	1,36

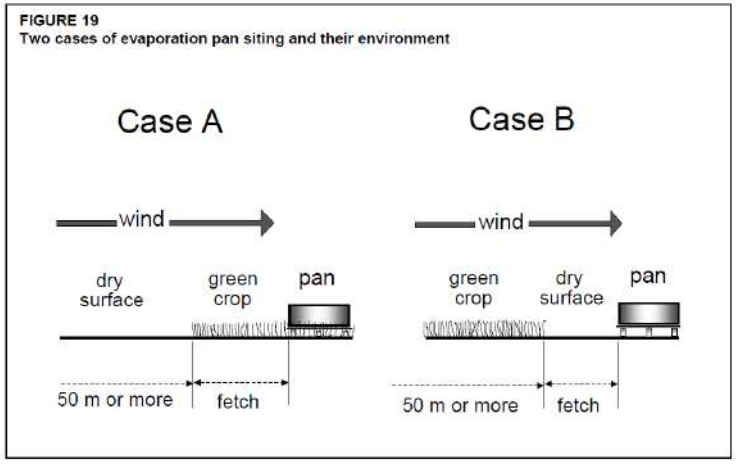
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IS with evaporation pans

Class A evaporation pan











Details in Doorenbos and Pruitt (1977) and Allen et al. (1998)

Allen R, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration – Guidelines for computing crop water requirements- FAO irrigation and drainage paper 56, FAO, Rome.

Doorenbos J, Pruitt WO. 1977. Guidelines for prediction of crop water requirements. FAO irrigation and drainage paper N°. 24, 2nd edition. FAO, Rome.

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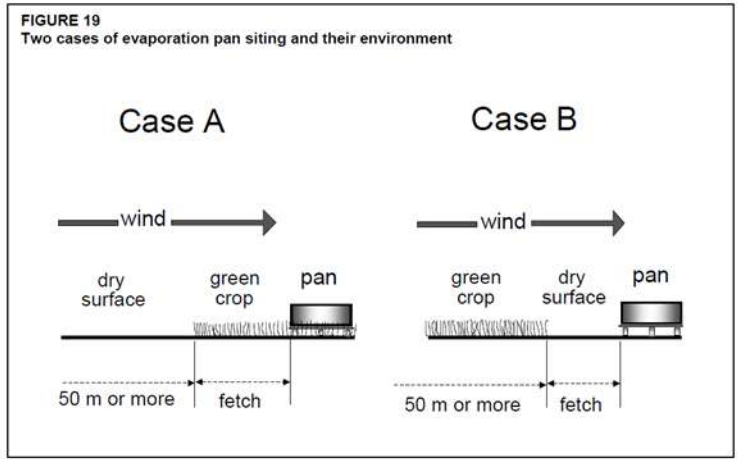
IS with evaporation pans

Class A evaporation pan



$$ET_o = K_p \times E_p \quad (mm)$$

E_p (mm) = pan evaporation
K_p = pan coefficient



SOURCE: Allen et al. (1988)

TABLE 5
Pan coefficients (K_p) for Class A pan for different pan siting and environment and different levels of mean relative humidity and wind speed (FAO Irrigation and Drainage Paper No. 24)

Class A pan	Case A: Pan placed in short green cropped area				Case B: Pan placed in dry fallow area			
RH mean (%) →		low < 40	medium 40 -70	high > 70		low < 40	medium 40 -70	high > 70
Wind speed (m s^{-1})	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light	1	.55	.65	.75	1	.7	.8	.85
< 2	10	.65	.75	.85	10	.6	.7	.8
	100	.7	.8	.85	100	.55	.65	.75
	1 000	.75	.85	.85	1 000	.5	.6	.7
Moderate	1	.5	.6	.65	1	.65	.75	.8
2-5	10	.6	.7	.75	10	.55	.65	.7
	100	.65	.75	.8	100	.5	.6	.65
	1 000	.7	.8	.8	1 000	.45	.55	.6
Strong	1	.45	.5	.6	1	.6	.65	.7
5-8	10	.55	.6	.65	10	.5	.55	.65
	100	.6	.65	.7	100	.45	.5	.6
	1 000	.65	.7	.75	1 000	.4	.45	.55
Very strong	1	.4	.45	.5	1	.5	.6	.65
> 8	10	.45	.55	.6	10	.45	.5	.55
	100	.5	.6	.65	100	.4	.45	.5
	1 000	.55	.6	.65	1 000	.35	.4	.45

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IS with evaporation pans

Class A evaporation pan



$ET_o = K_p \times E_p$ (mm)

E_p (mm) = pan evaporation
K_p = pan coefficient

$ET_c = K_c \times K_p \times E_p$ (mm)

TABLE 12
Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non stressed, well-managed crops in subhumid climates ($RH_{min} \approx 45\%$, $u_2 \approx 2$ m/s) for use with the FAO Penman-Monteith ET_o.

Crop	$K_{c\ ini}$ [1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum Crop Height (h) (m)
a. Small Vegetables	**0.7**	**1.05**	**0.95**	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6
Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions - dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3
b. Vegetables – Solanum Family (*Solanaceae*)	**0.6**	**1.15**	**0.80**	
Egg Plant		1.05	0.90	0.8
Sweet Peppers (bell)		1.05[2]	0.90	0.7
Tomato		1.15[2]	0.70-0.90	0.6
c. Vegetables – Cucumber Family (*Cucurbitaceae*)	**0.5**	**1.00**	**0.80**	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber – Fresh Market	0.6	1.00[2]	0.75	0.3
– Machine harvest	0.5	1.00	0.90	0.3
Pumpkin, Winter Squash		1.00	0.80	0.4
Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1.00	0.75	0.4
d. Roots and Tubers	**0.5**	**1.10**	**0.95**	
Beets, table		1.05	0.95	0.4
Cassava – year 1	0.3	0.80[3]	0.30	1.0
– year 2	0.3	1.10	0.50	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75[4]	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.10	0.95	0.6
Sugar Beet	0.35	1.20	0.70[5]	0.5

continued...

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IS with evaporation pans

atmosphere

Atmosphere **2022**, *13*, 1322. https://doi.org/10.3390/atmos13081322

MDPI

Article

Conversion Coefficient Analysis and Evaporation Dataset Reconstruction for Two Typical Evaporation Pan Types—A Study in the Yangtze River Basin, China

Ziheng Li, Xuefeng Sang *, Siqi Zhang, Yang Zheng and Qiming Lei

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

* Correspondence: sangxf@iwhr.com



Figure 1. Two types of evaporation pans: 20 cm diameter evaporation pan (**a**); E601 evaporation pan (b).

The coefficients of Allen et al. (1998) (the FAO56 monograph) cannot be used with these pans.

Uncertainty leads to irrigation treatments over 100 % ET_c. e.g. 125 % ET_c, 150 % ET_c, etc. This poses a conceptual problem.

Table 1. Detailed information on the two types of evaporation pans.

Name of Evaporimeter	Size	Description
D20	Area: 314 cm^2 (diameter: 20 cm) Depth: 10 cm	Rim is 70 cm from the ground, in every meteorological station in China
E601	Area: 3000 cm^2 Depth: 60 cm (cylinder) C + 8.7 cm (circular cone)	fiberglass material, surrounded by water and soil circle. Installed in every meteorological station from 1998

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IS from meteorological measurements



PROS:

- Cheap (low instrumentation requirements)
- It can be used by growers
- If well adjusted, it provides reliable values of ET_c

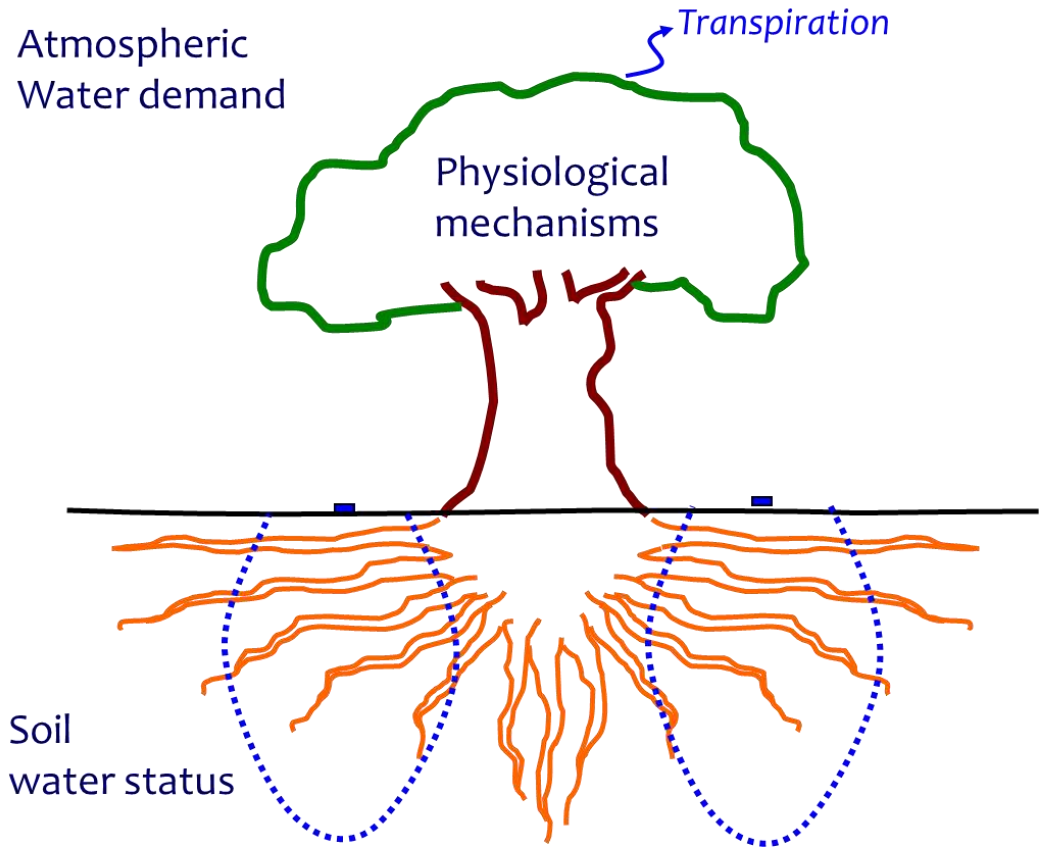
CONS:

- The CC approach is empirical. Safe extrapolation of K_c values to other orchards is not ensured

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IS from plant-based measurements





When measuring a plant variable related to its water stress, we use the plant as a biosensor that integrates the soil and atmospheric water status, as well as the physiology of the plant.

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IS from plant-based measurements

Most widely used methods:

1. Non-automated





2. Automated






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IS from plant-based measurements

Other approaches:

Stem water content

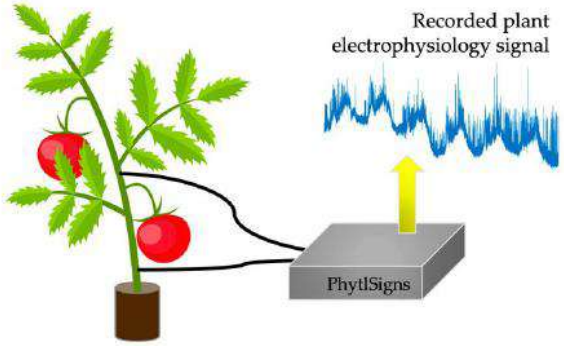


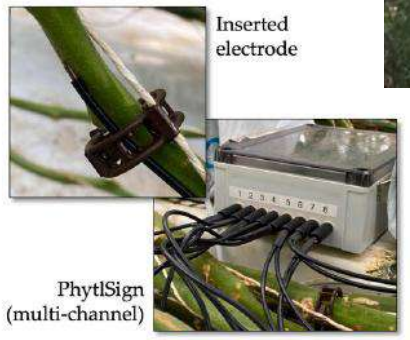


Leaf water content



Electrical potential





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IS from plant-based measurements

Most widely used methods:

1. Non-automated





2. Automated






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SI from stem water potential and stomatal conductance

Agricultural Water Management 112 (2012) 43–54

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Midday stem water potential as a useful tool for estimating irrigation requirements in olive trees

A. Moriana[a,*], D. Pérez-López[b], M.H. Prieto[c], M. Ramírez-Santa-Pau[d], J.M. Pérez-Rodriguez[c]

[a] Departamento de Ciencias Agroforestales, Escuela Técnica Superior de Ingeniería Agronómica, University of Seville, Crta. de Utrera, Km 1, 41013 Sevilla, Spain
[b] Departamento de Producción Vegetal, Escuela de Ingeniería Técnica Agrícola, Technical University of Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain
[c] Departamento de Hortofruticultura, Centro de Investigación "La Orden-Valdesequera", Junta de Extremadura, A
[d] Private Agricultural Consultant, Madrid, Spain









Irrigation Science
https://doi.org/10.1007/s00271-019-00623-9

Check for updates

Estimation of stomatal conductance and stem water potential threshold values for water stress in olive trees (cv. Arbequina)

L. Ahumada-Orellana[1] · S. Ortega-Farías[1,2] · C. Poblete-Echeverría[3] · P. S. Searles[4]

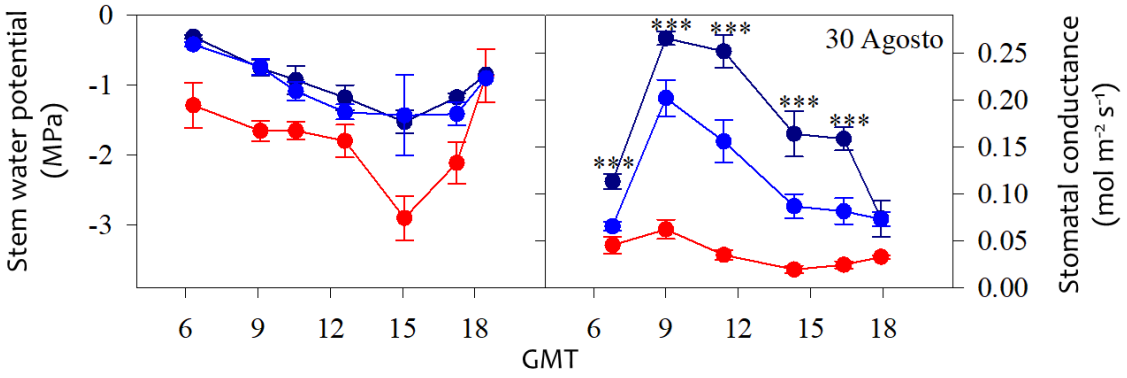
Received: 27 July 2018 / Accepted: 2 February 2019
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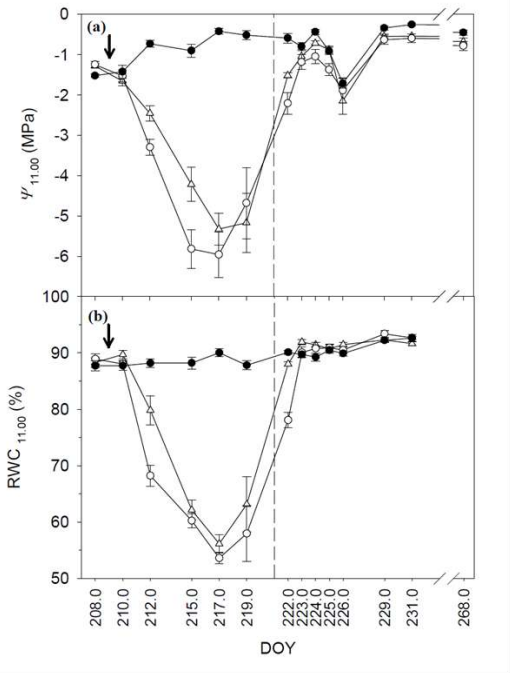
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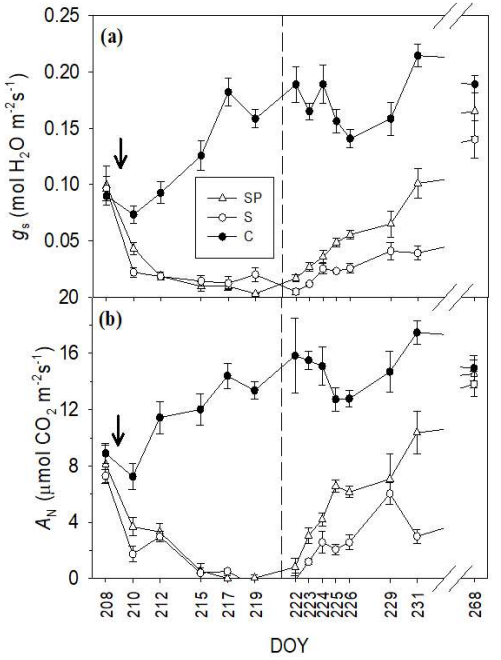
SI from stem water potential and stomatal conductance

Whatch out! Ψ_{leaf} and Ψ_{stem} can lead to erros on the actual plant water status in two cases:

- Isohydric behaviour of the sampled plant
- During recovery after a long period under water stress







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SI from stem water potential and stomatal conductance

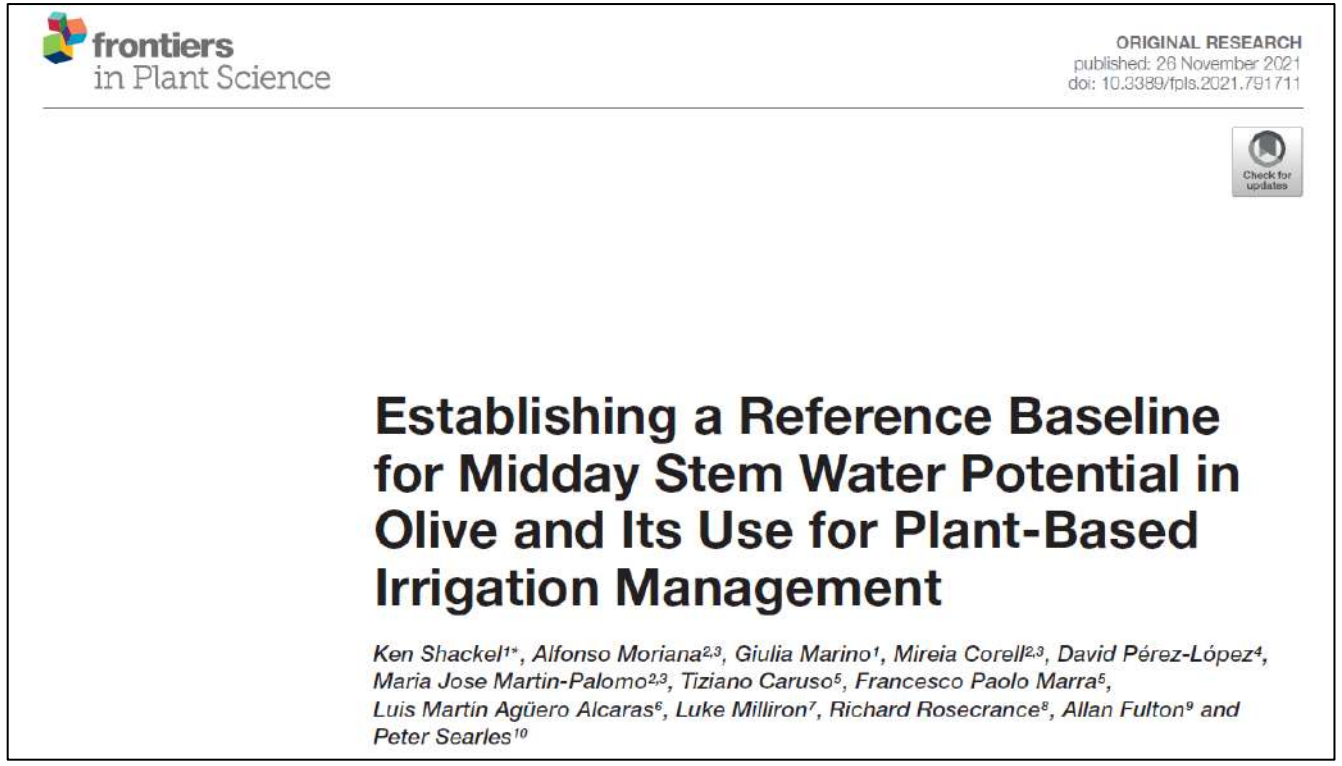
The user must know the thresholds for water stress

For olive: Ψ_{pd} = - 0.5 MPa

$\Psi_{min\text{-}leaf}$ = - 1.2 MPa (low fruit load)

- 1.4 MPa (high " ")

g_s = 0.20 mol m^{-2} s^{-1}



frontiers in Plant Science

ORIGINAL RESEARCH
published: 26 November 2021
doi: 10.3389/fpls.2021.791711

Check for updates

Establishing a Reference Baseline for Midday Stem Water Potential in Olive and Its Use for Plant-Based Irrigation Management

Ken Shackel[1], Alfonso Moriana[2,3], Giulia Marino[1], Mireia Corell[2,3], David Pérez-López[4], Maria Jose Martin-Palomo[2,3], Tiziano Caruso[5], Francesco Paolo Marra[5], Luis Martín Agüero Alcaras[6], Luke Milliron[7], Richard Rosecrance[8], Allan Fulton[9] and Peter Searles[10]*

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SI from stem water potential and stomatal conductance

PSY1 Stem Psychrometer (ICT Int.)



Florapulse microtensiometer



FloraPulse : the most accurate irrigation guidance for orchards and vineyards

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SI from stem water potential and stomatal conductance





Agricultural and Forest Meteorology 218–219 (2016) 92–101

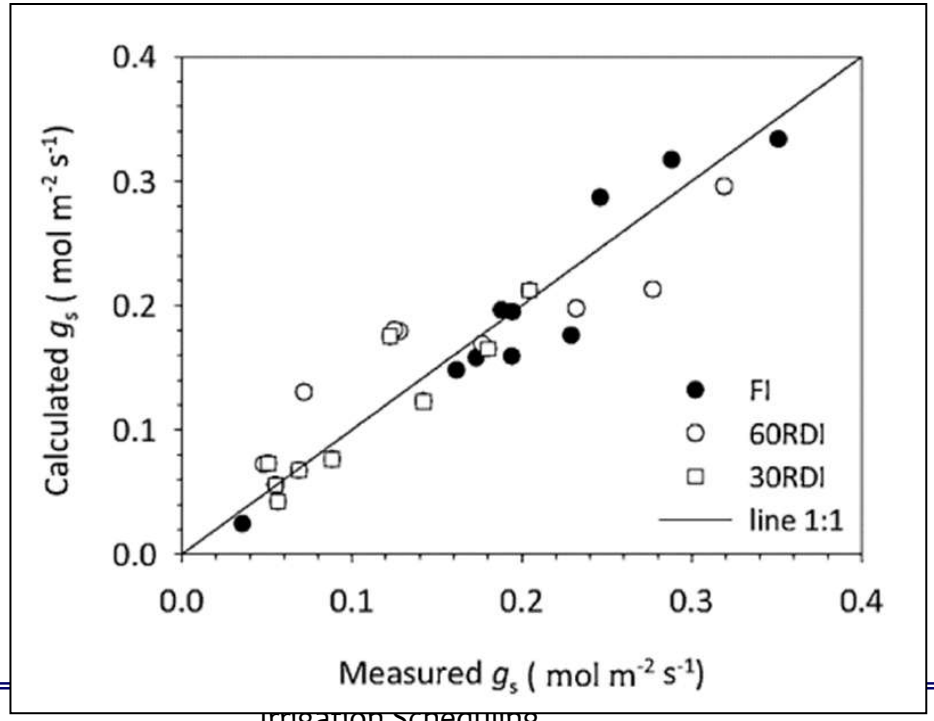
Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit

V. Hernandez-Santana[a], J.E. Fernández[a], C.M. Rodriguez-Dominguez[a,b], R. Romero[a], A. Diaz-Espejo[a,*]



$g_s \approx J_s / D_a$

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SI from stem water potential and stomatal conductance







PROS:

- Variables highly informative
- Little data processing

CONS:

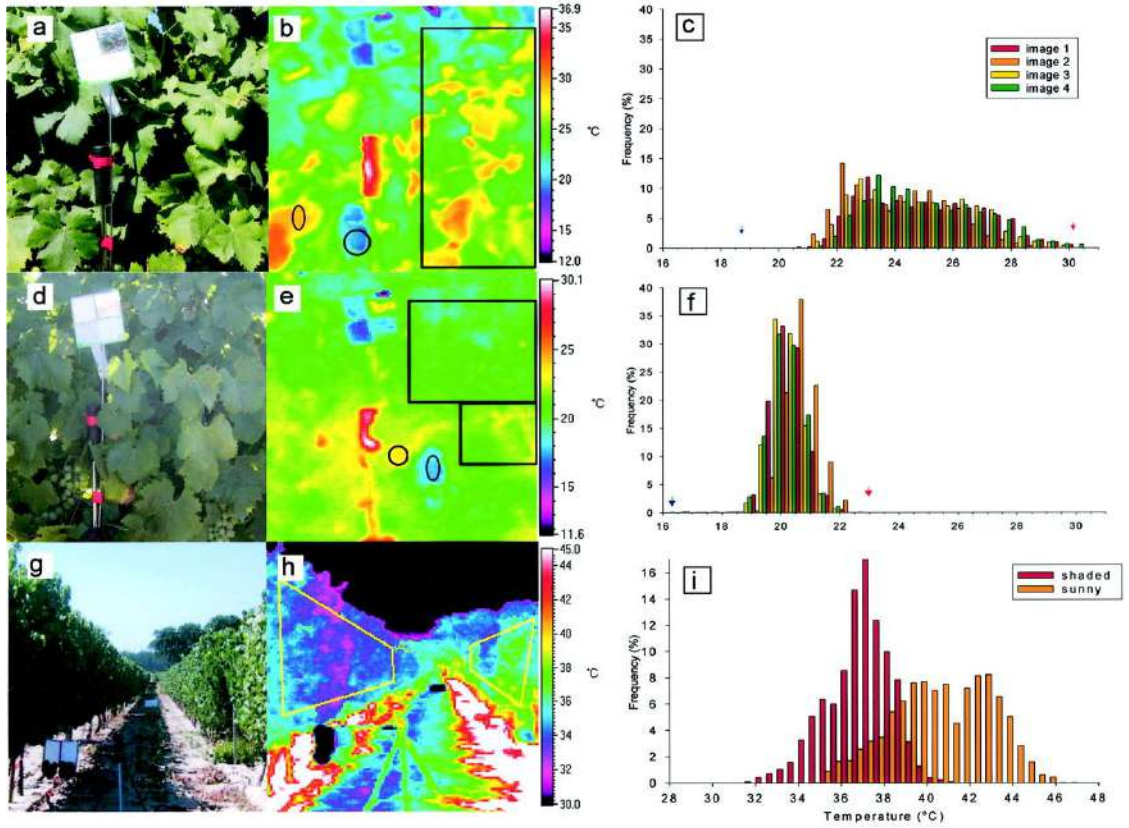
- Difficult automation (*)
- Knowledge on plant physiology required
- Too expensive: operator + vehicle + + instrument + consumables

* Stomatal conductance can de derived from automatic sap flow measurements, and the stem water potential can be derived from the use of microtensiometers or psychrometers.

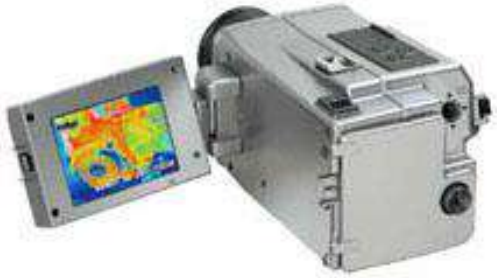
Enrique Fernández
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SI from canopy temperature

T_c is linked to transpiration



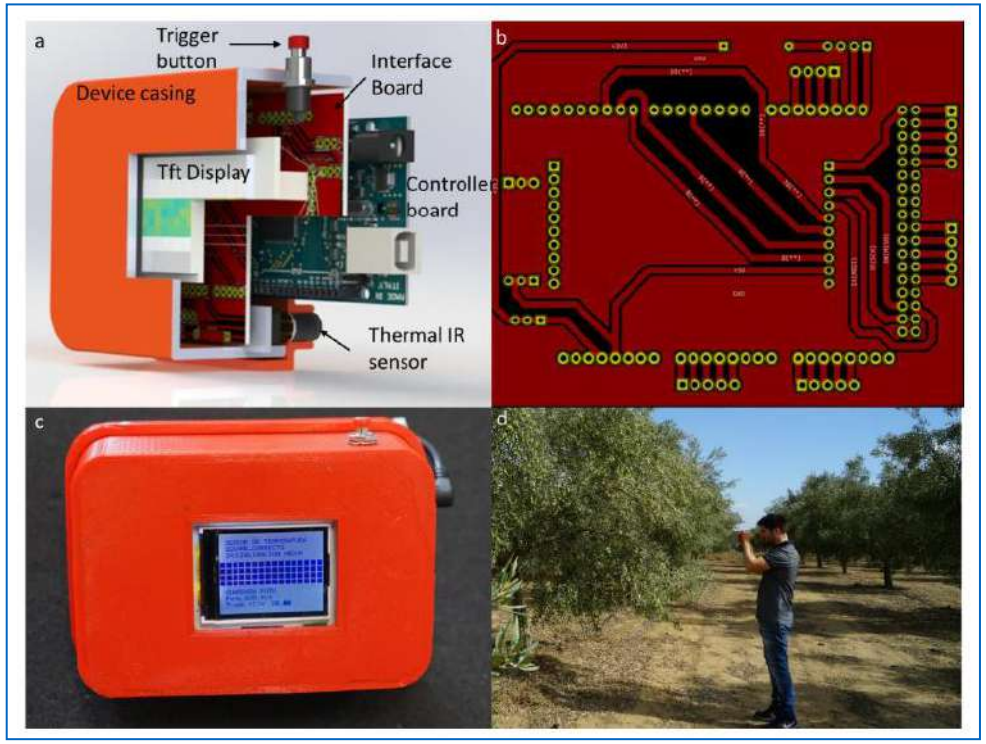






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SI from canopy temperature



remote sensing

MDPI

Article

A New Low-Cost Device Based on Thermal Infrared Sensors for Olive Tree Canopy Temperature Measurement and Water Status Monitoring

Miguel Noguera [1], Borja Millán [1,*], Juan José Pérez-Paredes [2], Juan Manuel Ponce [1], Arturo Aquino [1] and José Manuel Andújar [1]

1 University of Huelva, Department of Electronic Engineering, Computer Systems and Automation, La Rábida, Palos de la Frontera, 21819 Huelva, Spain; miguel.noguera@diesia.uhu.es (M.N.); jmponce.real@diesia.uhu.es (J.M.P.); arturo.aquino@diesia.uhu.es (A.A.); andujar@diesia.uhu.es (J.M.A.)

2 Chapingo Autonomous University, Post-graduate program in Agricultural Engineering and Integral Water Use, Chapingo, 56227, Mexico; al18129294@chapingo.mx

* Correspondence: borja.millan@diesia.uhu.es; Tel.: +34 959-217-64

Received: 16 December 2019; Accepted: 21 February 2020; Published: 22 February 2020

check for updates

SI from canopy temperature



PROS:

- Relatively cheap
- Taking the images is easy

CONS:

- Heavy data processing
- Data interpretation is far form easy

A key step for the success of this approach is the development of effective algorithms to process the images.

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SI from canopy temperature

Original article

Fruits, 2012, vol. 67, p. 463–474 © 2012

Approach to assess infrared thermal imaging of almond trees under water-stress conditions

Iván García-Tejero, Víctor Hugo Durán-Zuazo, Javier Arriaga, Almudena Hernández, Luisa Maria Vélez, José Luis Muriel-Fernández

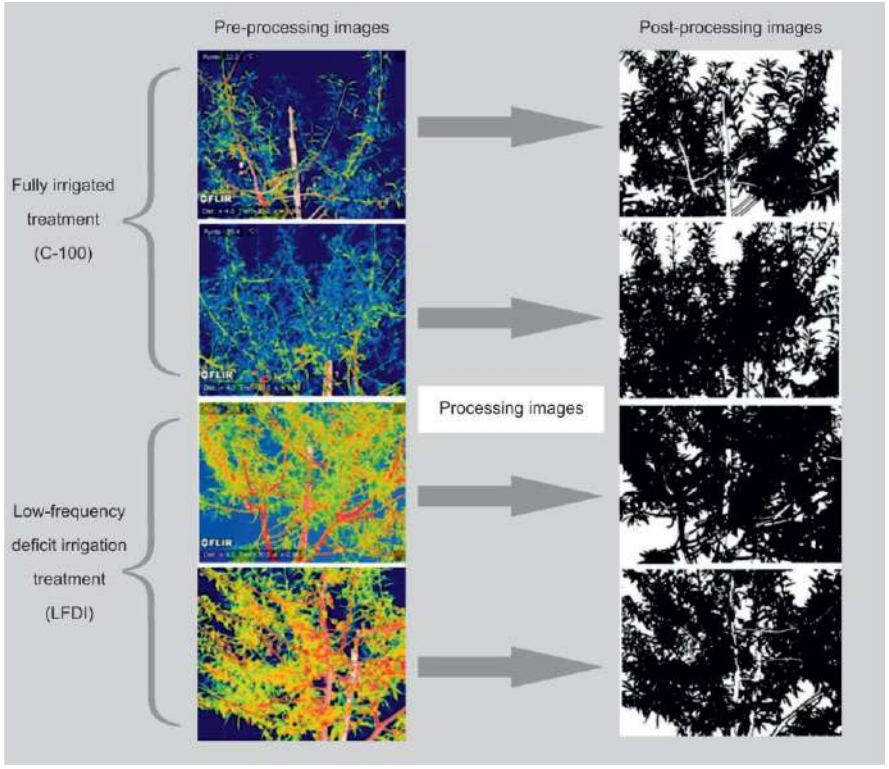


Figure 4.
Relationship between temperature variation (ΔT) and stem-water potential (Ψ_{Stem}) for almond trees.

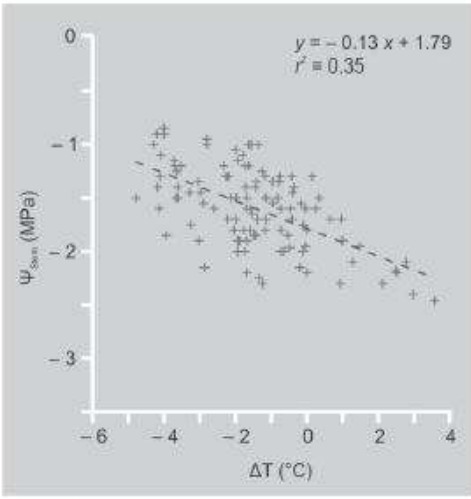
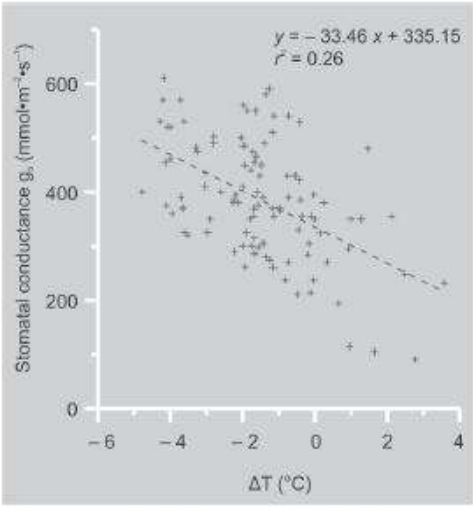


Figure 5.
Relationship between temperature variation (ΔT) and stomatal conductance (g_S) for almond trees.



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SI from canopy temperature

Agricultural Water Management 187 (2017) 210–221

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

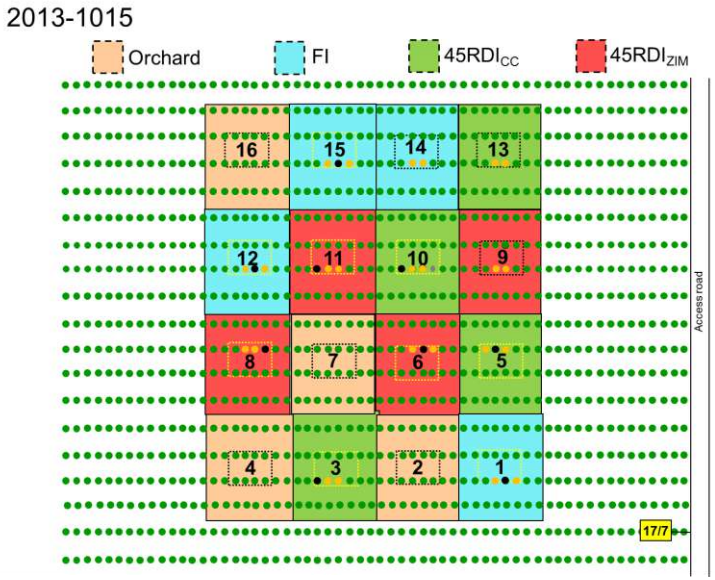
Research Paper

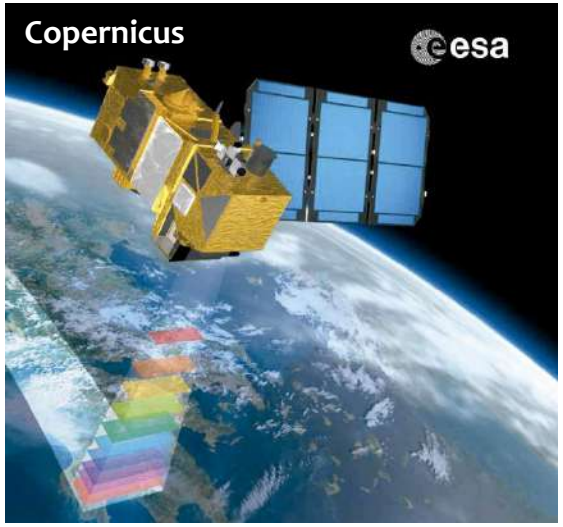
Assessing a crop water stress index derived from aerial thermal imaging and infrared thermometry in super-high density olive orchards

Gregorio Egea[a,*], Carmen M. Padilla-Díaz[b], Jorge Martinez-Guanter[a], José E. Fernández[b], Manuel Pérez-Ruiz[a]

[a] Area of Agroforestry Engineering, Aeroespace Engineering and Fluids Mechanic Department, School of Agricultural Engineering, Universidad de Sevilla, Ctra. Utrera km.1, 41013 Seville, Spain

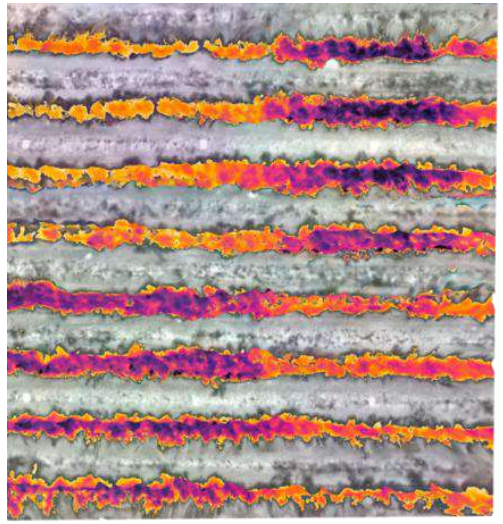
[b] Irrigation and Crop Ecophysiology Group, Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC), Avenida Reina Mercedes 10, 41012, Seville, Spain











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IS from plant-based measurements

Most widely used methods:

1. Non-automated





2. Automated






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IS from automated plant-based measurements

Sap flow, trunk diameter variations and leaf turgor pressure have been widely tested.







- The plant is used as a biosensor

Required for PI
- Continuos and automatic data recording
- Sensors are implemented with data transmission systems

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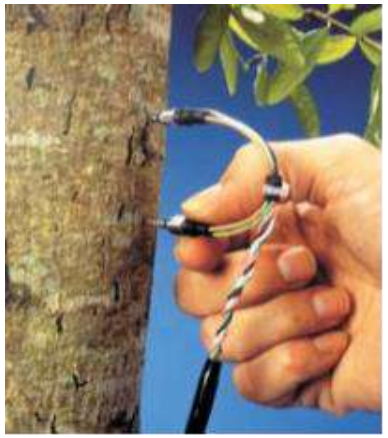
SI from sap flow measurements

A number of methods are available

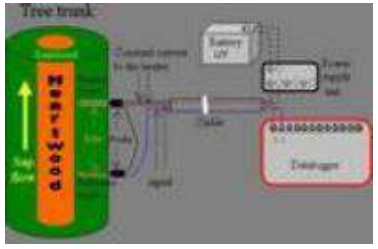
https://www.ishs.org/sap-flow/ishs-working-group-sap-flow-online-resources















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SI from sap flow measurements

Plant Soil (2008) 305:91–104
DOI 10.1007/s11104-007-9348-8

REGULAR ARTICLE

The use of sap flow measurements for scheduling irrigation in olive, apple and Asian pear trees and in grapevines

J. E. Fernández · S. R. Green · H. W. Caspari · A. Diaz-Espejo · M. V. Cuevas

The main problem of using SF measurements to schedule irrigation is that they require heavy data processing

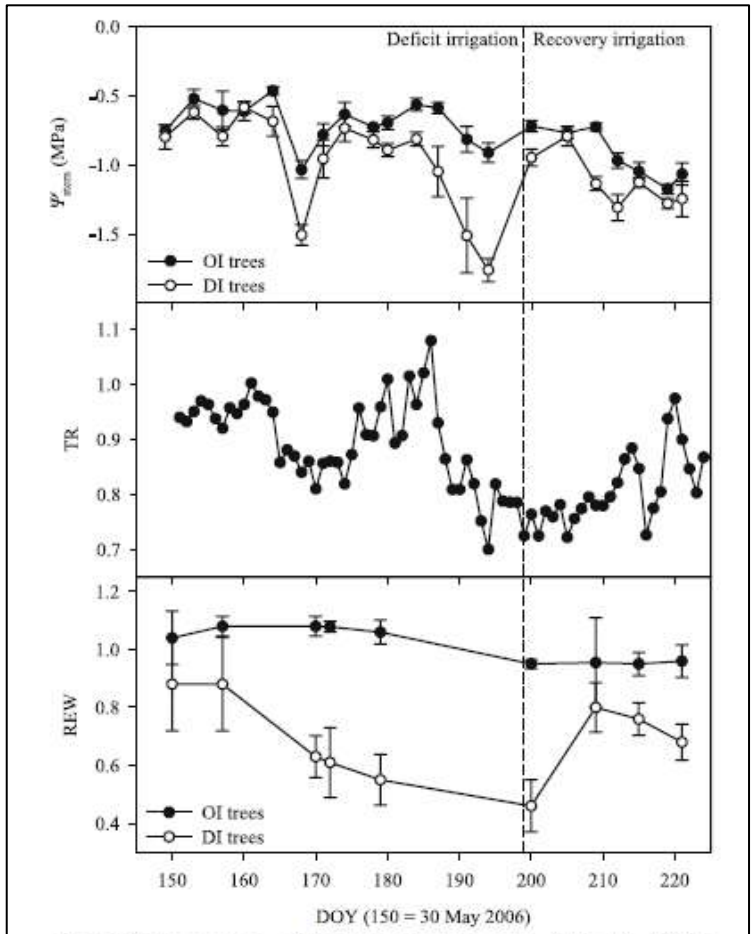


Fig. 6 Time course of the transpiration ratio (TR=E_p deficit irrigated trees/E_p overirrigated trees, being E_p the daily plant water use estimated from sap flow measurements) calculated from measurements in the olive trees of Experiment 1 (see text for details). Also shown are the stem water potential (Ψ_{stem}) of the instrumented trees, and the relative extractable water values (REW) for each treatment. *DI* Deficit irrigated, *OI* over-irrigated. The *dash line* represents the change in the irrigation regime of the DI trees (see text for details). Data points are the average of three values; *vertical bars* represent±the standard error

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IS from Trunk Diameter Variation measurements

Holders of Al and INVAR (alloy of Ni and Fe with minimal thermal expansion)



Linear Variable Displacement/Differential Transducers/Transformers (LVDT sensors)

The "Plantsens" dendrometer



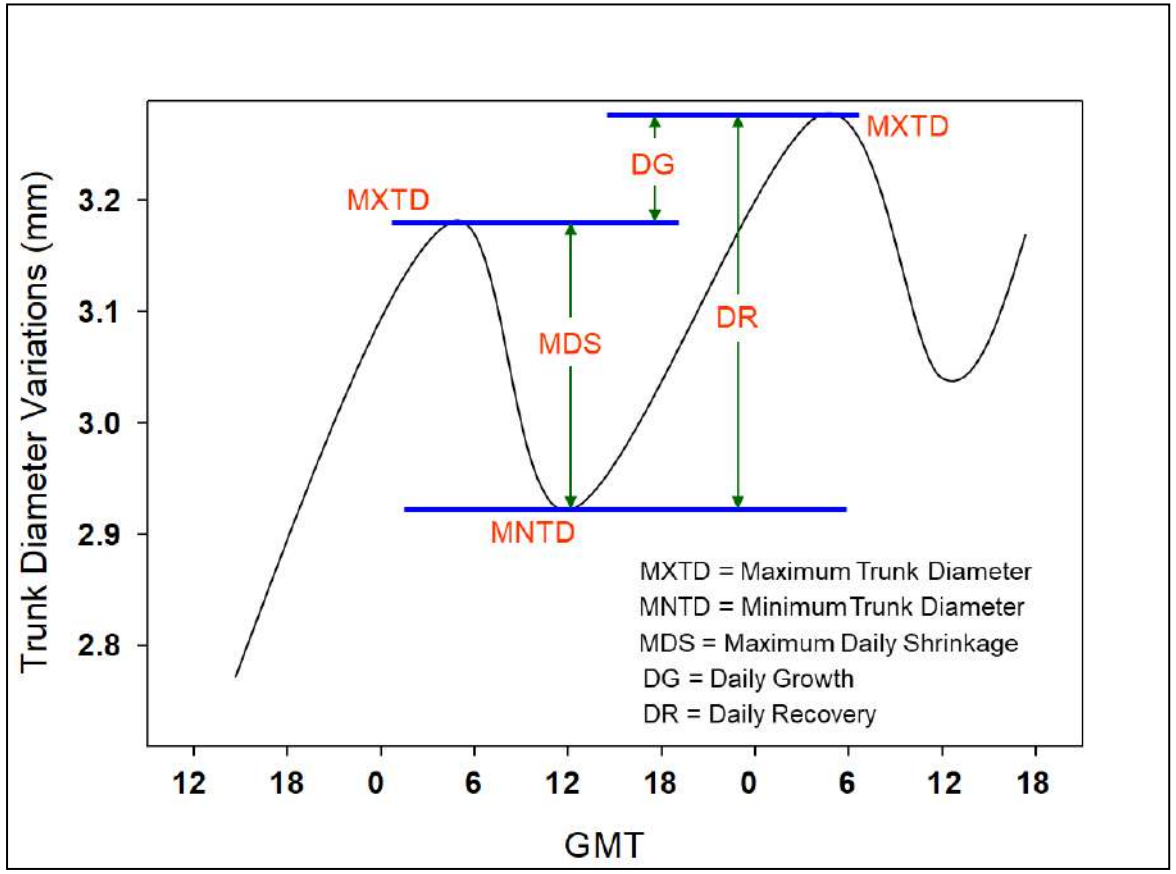
Related system



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IS from Trunk Diameter Variation measurements

Measurements every 2s
Average values stored every 15 min



SOURCE: Fernández, J.E., Cuevas, M.V., 2010. Irrigation scheduling from stem diameter variations: a review. Agricultural and Forest Meteorology 150, 135-151.

Choosing the right water stress index is crucial for the success of IS from TDV

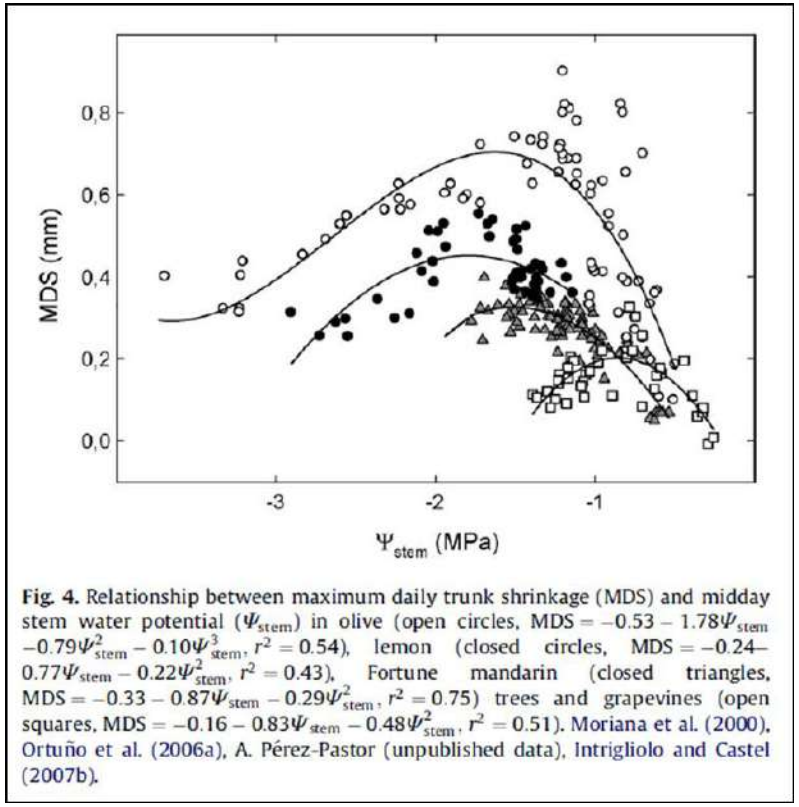


Fig. 4. Relationship between maximum daily trunk shrinkage (MDS) and midday stem water potential (Ψ_{stem}) in olive (open circles, MDS = $-0.53 - 1.78\Psi_{stem} - 0.79\Psi^2_{stem} - 0.10\Psi^3_{stem}$, $r^2 = 0.54$), lemon (closed circles, MDS = $-0.24 - 0.77\Psi_{stem} - 0.22\Psi^2_{stem}$, $r^2 = 0.43$), Fortune mandarin (closed triangles, MDS = $-0.33 - 0.87\Psi_{stem} - 0.29\Psi^2_{stem}$, $r^2 = 0.75$) trees and grapevines (open squares, MDS = $-0.16 - 0.83\Psi_{stem} - 0.48\Psi^2_{stem}$, $r^2 = 0.51$). Moriana et al. (2000), Ortuño et al. (2006a), A. Pérez-Pastor (unpublished data), Intrigliolo and Castel (2007b).

SOURCE: M.F. Ortuño et al. (2010). Could trunk diameter sensors Be used in woody crops for irrigation scheduling? A review of current knowledge and future perspectives. Agricultural Water Management 97, 1-11.

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IS from Trunk Diameter Variation measurements

Agricultural Water Management 97 (2010) 1293–1302

Contents lists available at ScienceDirect

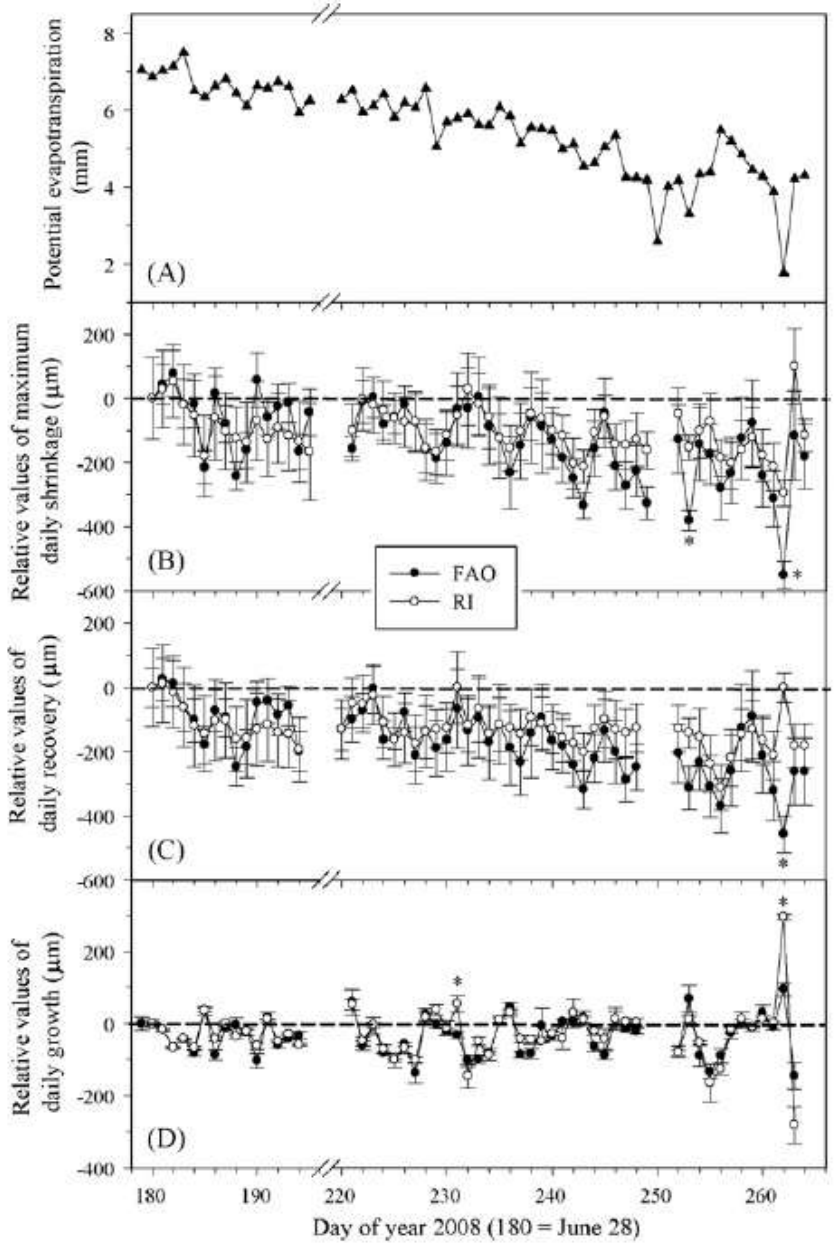
Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Assessment of trunk diameter variation derived indices as water stress indicators in mature olive trees

M.V. Cuevas[a], J.M. Torres-Ruiz[a], R. Álvarez[b], M.D. Jiménez[b], J. Cuerva[b], J.E. Fernández[a,*]

[a] Instituto de Recursos Naturales y Agrobiología (IRNASE-CSIC), Avenida de Reina Mercedes, nº 10, 41012 Seville, Spain
[b] Verdtech Nuevo Campo S.A., Avenida Dehesa del Piorno, 1, Polígono Industrial La Gravera, 21440 Lepe, Spain



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IS from Trunk Diameter Variation measurements

22 year-old ‘Arbequina’ trees, 7 m × 6 m



Agricultural Water Management 97 (2010) 1293–1302

Contents lists available at ScienceDirect

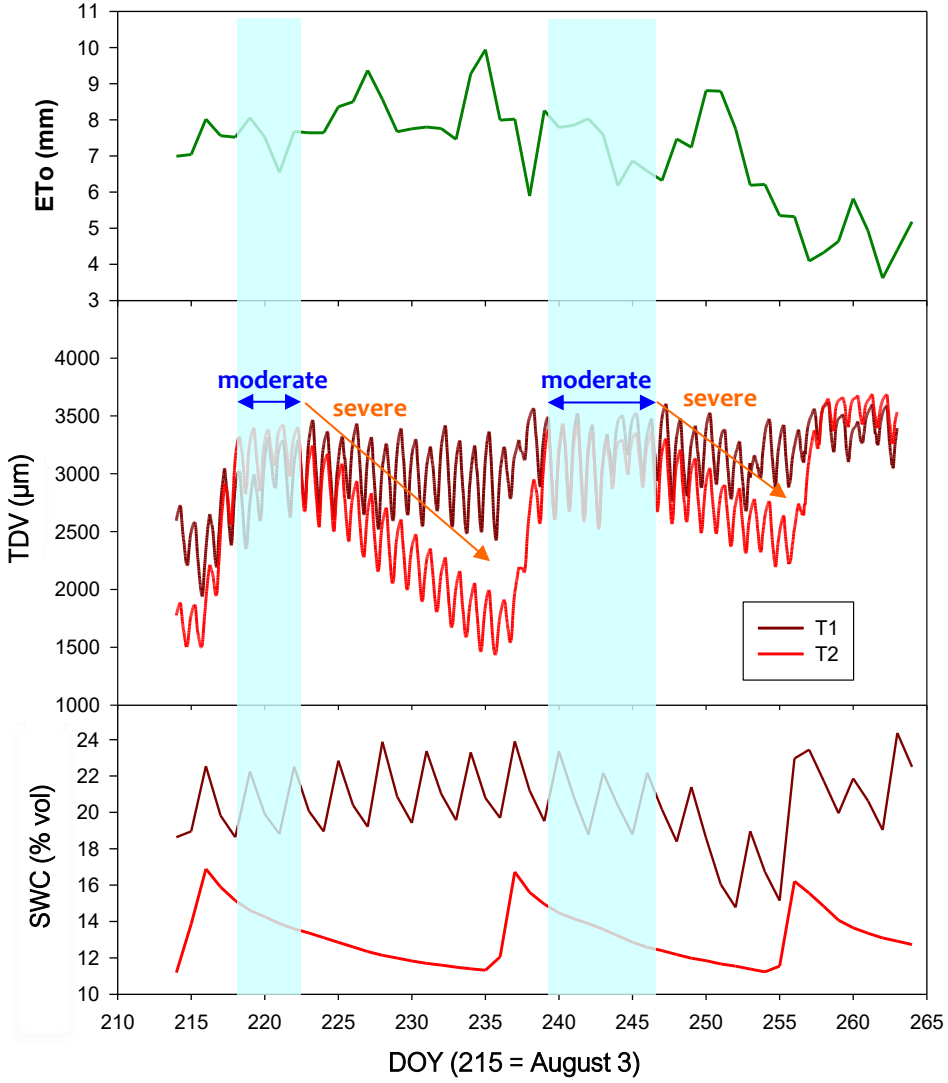
Agricultural Water Management

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Assessment of trunk diameter variation derived indices as water stress indicators in mature olive trees

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[b] Verdtech Nuevo Campo S.A., Avenida Dehesa del Fiorno, 1, Polígono Industrial La Gravera, 21440 Lepe, Spain





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IS from TDV and SF measurements

Agricultural Water Management 98 (2011) 1813–1821

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Use of maximum trunk diameter measurements to detect water stress in mature 'Arbequina' olive trees under deficit irrigation

J.E. Fernández [a,*], J.M. Torres-Ruiz [a], A. Diaz-Espejo [a], A.
J. Cuerva [b], M.V. Cuevas [a]

[a] Instituto de Recursos Naturales y Agrobiología (IRNASE-CSIC), Avenida de Reina Mercedes no
[b] Verdtech Nuevo Campo S.A., Avenida Dehesa del Piorno, 1 Polígono Industrial la Gravera, 21

Agricultural Water Management 97 (2010) 1–11

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ps for irrigation scheduling?
ves

olo [d], C. Biel [e], C.D. Mellisho [a],
s [h], J. Bonany [i], A. Torrecillas [a,g,*]

Irrig Sci (2013) 31:729–746
DOI 10.1007/s00271-012-0357-x

ORIGINAL PAPER

Assessing water stress in a hedgerow olive orchard from sap flow and trunk diameter measurements

M. V. Cuevas · M. J. Martín-Palomo · A. Diaz-Espejo ·
J. M. Torres-Ruiz · C. M. Rodriguez-Dominguez ·
A. Perez-Martin · R. Pino-Mejías · J. E. Fernández

Agricultural Water Management 97 (201

Contents lists available at Scie

Agricultural Water Ma

journal homepage: www.elsevier.

Assessment of trunk diameter variation derived indices as water stress indicators in mature olive trees

M.V. Cuevas [a], J.M. Torres-Ruiz [a], R. Álvarez [b], M.D. Jiménez [b], J. Cuerva [b], J.E. Fernández [a,*]

[a] Instituto de Recursos Naturales y Agrobiología (IRNASE-CSIC), Avenida de Reina Mercedes, nº 10, 41012 Seville, Spain
[b] Verdtech Nuevo Campo S.A., Avenida Dehesa del Piorno, 1, Polígono Industrial La Gravera, 21440 Lepe, Spain

gy

formet

Agricultural and Forest Meteorology

review

Irrigation scheduling from stem diameter variations: A review

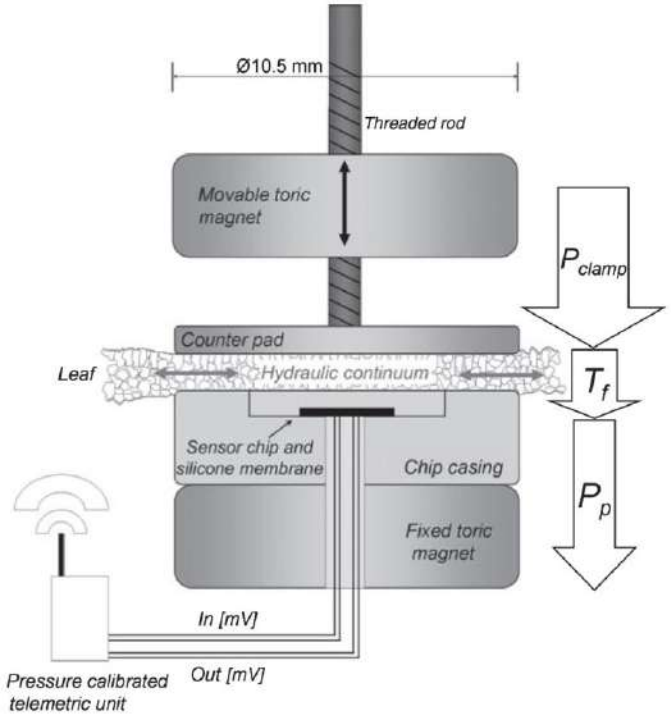
J.E. Fernández *, M.V. Cuevas

Instituto de Recursos Naturales y Agrobiología (IRNAS-CSIC), Avenida de Reina Mercedes, No. 10, 41012 Seville, Spain

SI from leaf turgor measurements

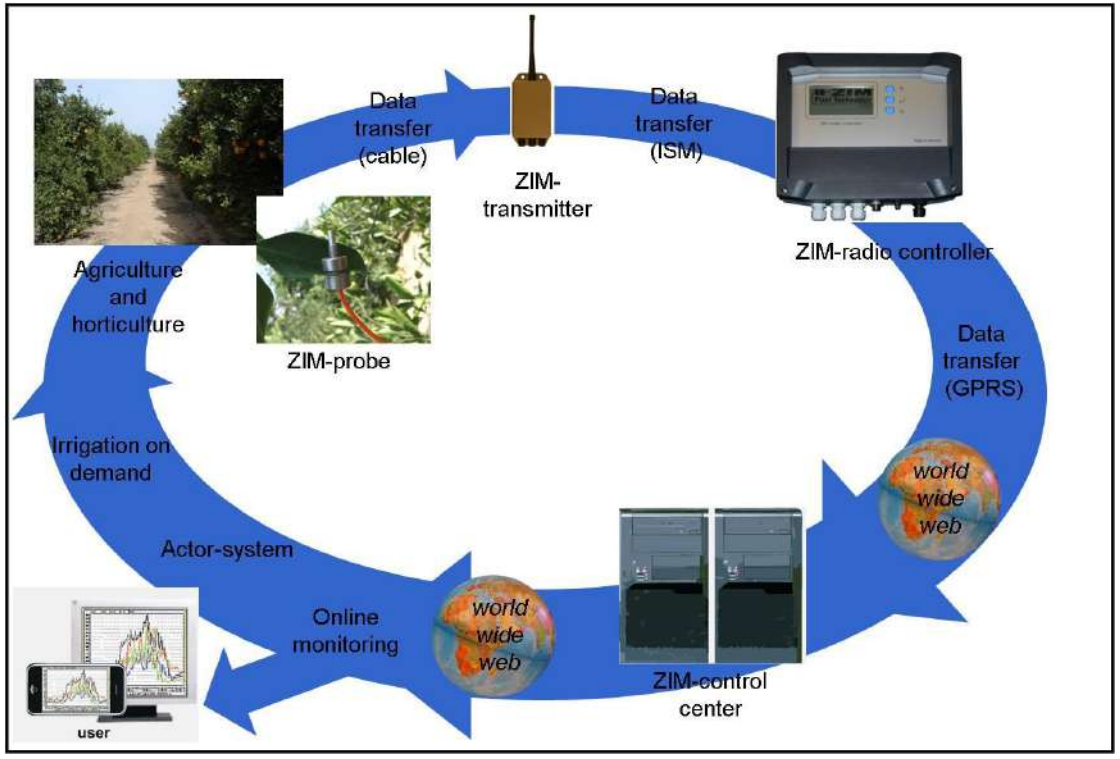


$\Psi_{leaf} = TP - \pi_o$



www.zim-plant-technology.com

Yara zim-plant-technology



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jefer@irnase.csic.es

SI from leaf turgor measurements

The ZIM probe









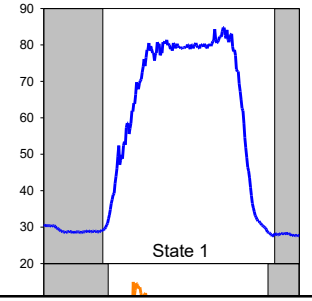




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SI from leaf turgor measurements





ψ_{stem} > -1.2 MPa



low stress

Agricultural Water Management 100 (2011) 25–35

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Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Online-monitoring of tree water stress in a hedgerow olive orchard using the leaf patch clamp pressure probe

J.E. Fernández[a,*], C.M. Rodriguez-Dominguez[a], A. Perez-Martin[a], U. Zimmermann[b], S. Rüger[b], M.J. Martín-Palomo[c], J.M. Torres-Ruiz[a], M.V. Cuevas[a], C. Sann[b,d], W. Ehrenberger[b,d], A. Diaz-Espejo[a]

[a] Instituto de Recursos Naturales y Agrobiología (IRNAS-CSIC), Apartado 1052, 41080 Sevilla, Spain
[b] ZIM Plant Technology GmbH, Neuendorfstr. 19, D-16761 Hennigsdorf, Germany
[c] ETSIA, Departamento de Ciencias Agroforestales, Carretera de Utrera, 41013 Sevilla, Spain
[d] Lehrstuhl für Biotechnologie, Biozentrum, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

Agricultural Water Management 164 (2016) 28–37

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Scheduling regulated deficit irrigation in a hedgerow olive orchard from leaf turgor pressure related measurements

C.M. Padilla-Díaz[a,*], C.M. Rodriguez-Dominguez[a,b], V. Hernandez-Santana[a], A. Perez-Martin[a], J.E. Fernández[a]

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[b] Departamento de Biología Vegetal y Ecología, Universidad de Sevilla, Avenida Reina Mercedes, 6, 41012 Sevilla, Spain

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SI from leaf turgor measurements

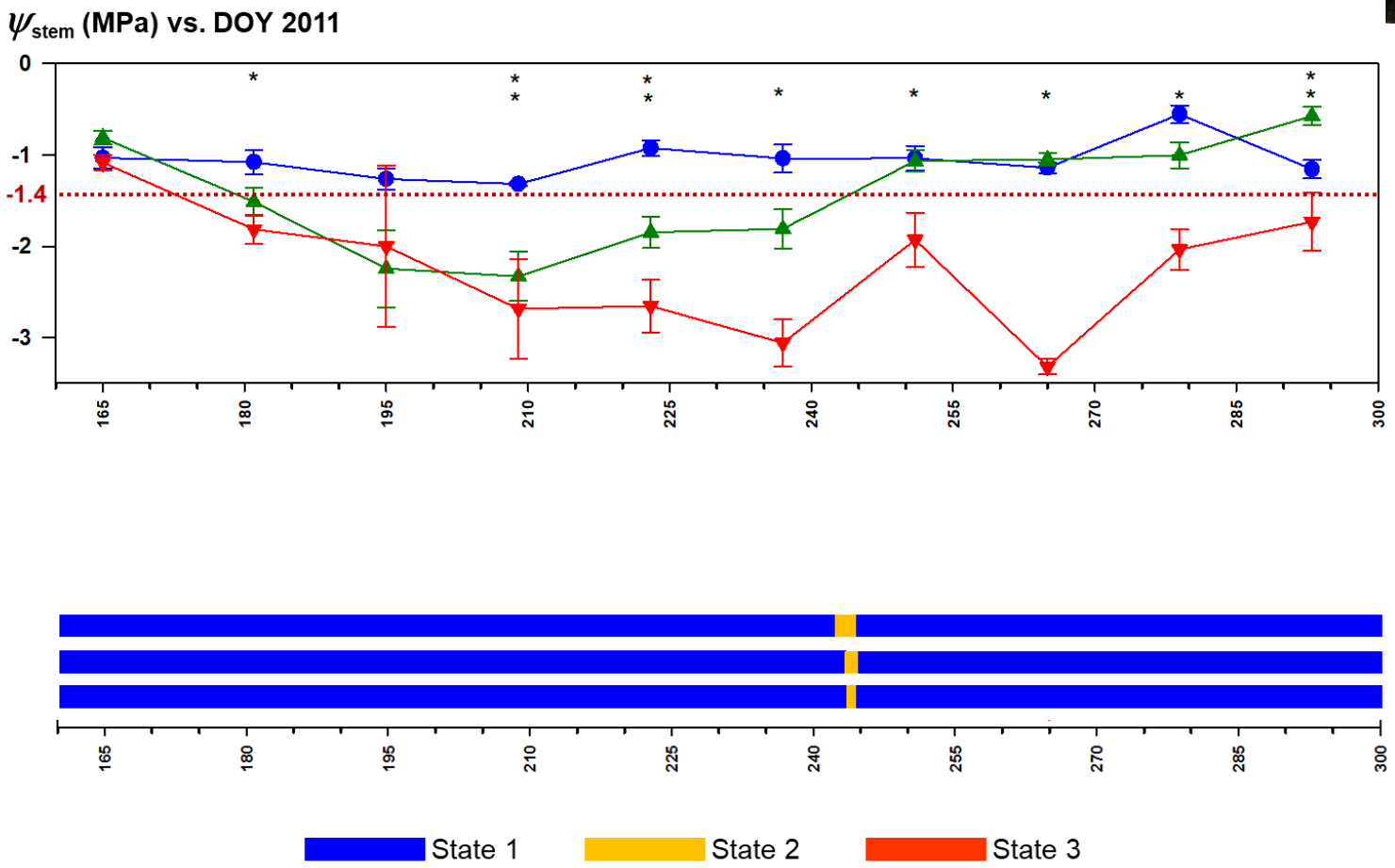


Sanabria orchard



Control: FI
T1: 60RDI
T2: 30RDI

FI



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SI from leaf turgor measurements

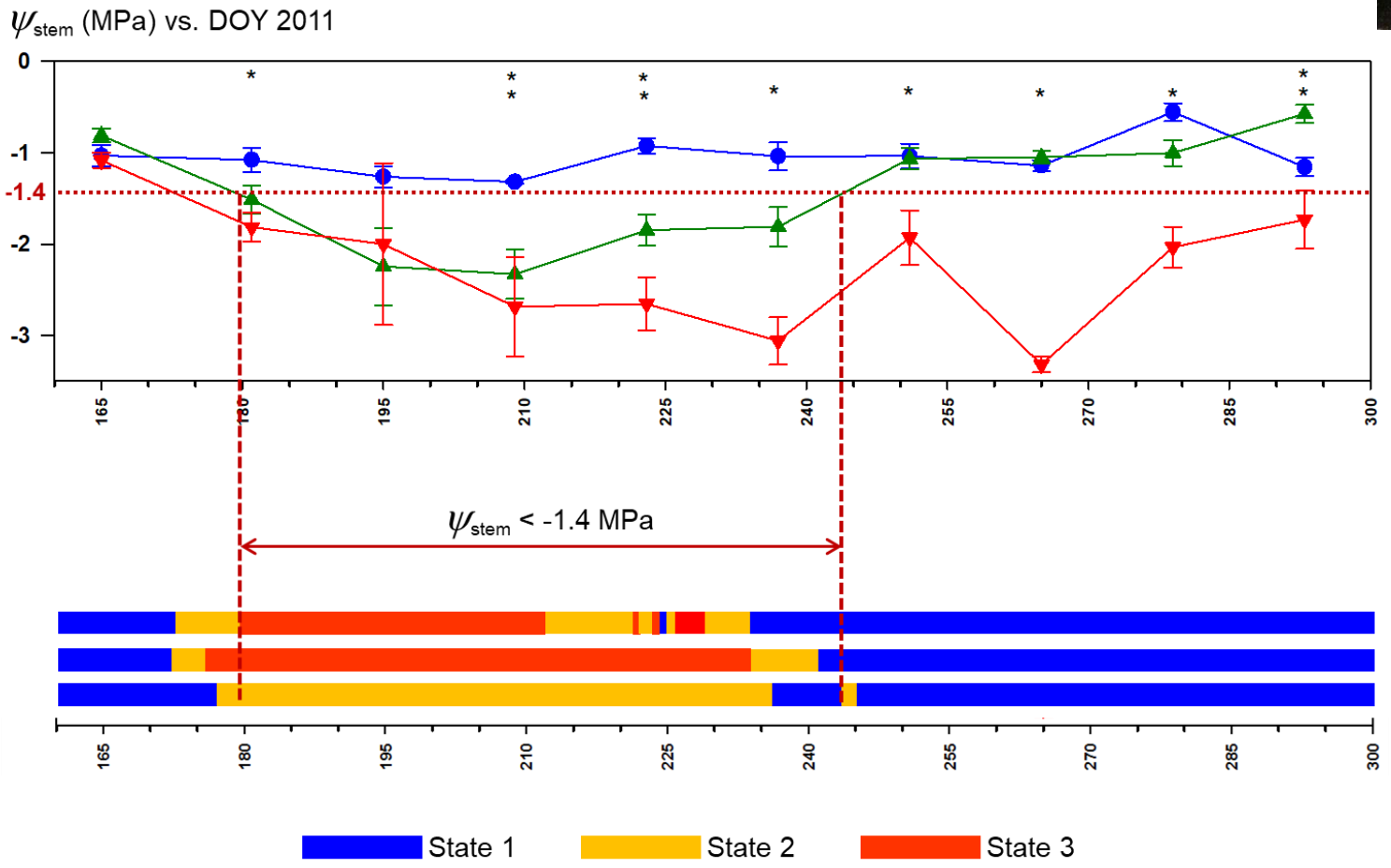


Sanabria orchard



Control: FI
T1: 60RDI
T2: 30RDI

60RDI



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SI from leaf turgor measurements

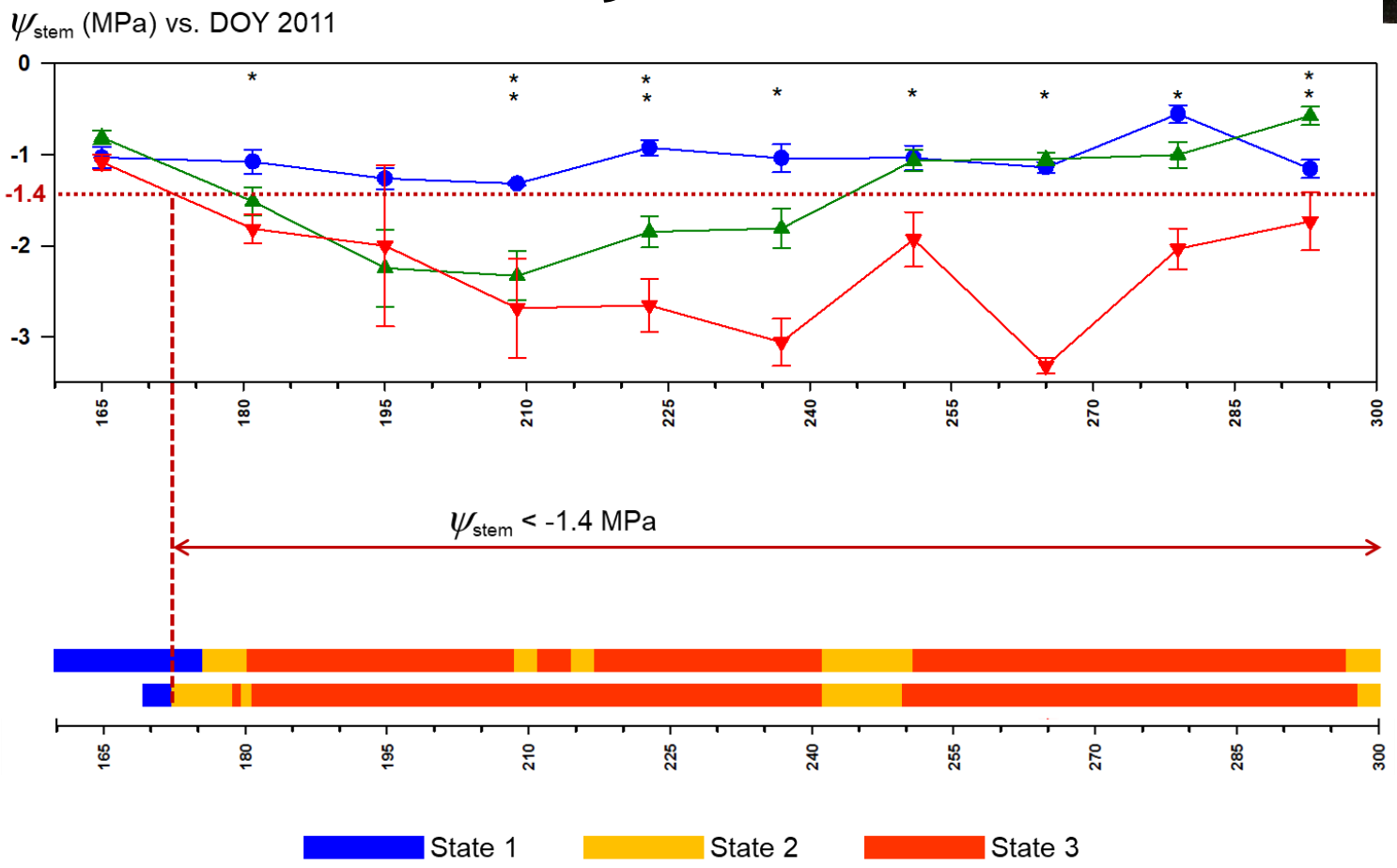


Sanabria orchard



Control: FI
T1: 60RDI
T2: 30RDI

30RDI



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SI from leaf turgor measurements

Electronics **2023**, *12*, 249. https://doi.org/10.3390/electronics12010249

electronics

MDPI

Article

Development of Non-Destructive Testing Device for Plant Leaf Expansion Monitoring

Xianchang Meng [1,2,3], Yili Zheng [1,2,3] and Weiping Liu [1,2,3,*]

1 School of Technology, Beijing Forestry University, Beijing 100083, China
2 Beijing Laboratory of Urban and Rural Ecological Environment, Beijing Municipal Education Commission, Beijing 100083, China
3 Key Lab of State Forestry Administration for Forestry Equipment and Automation, Beijing 100083, China
* Correspondence: hfpl916@126.com

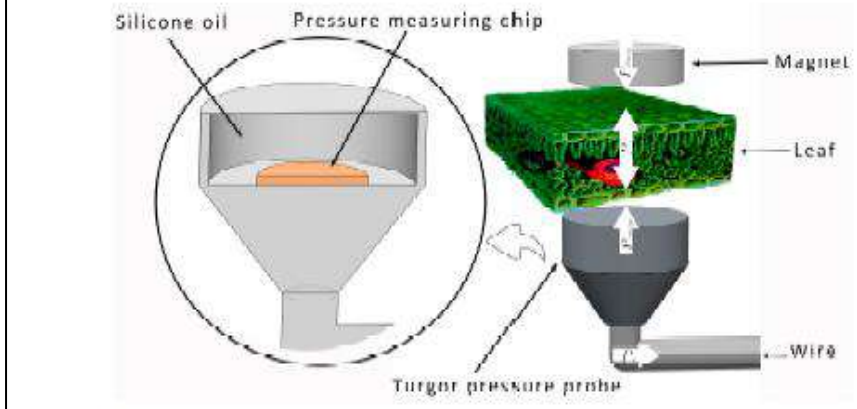
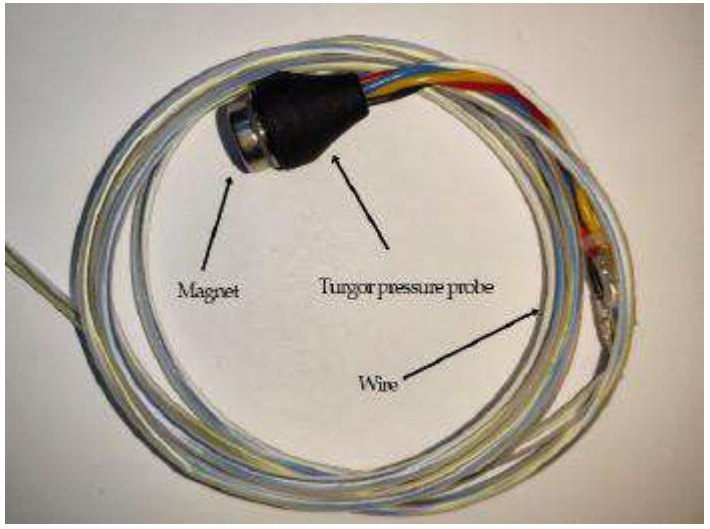


Figure 1. Sensor system structure diagram.





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SI from leaf turgor measurements

Journal of Experimental Botany, Page 1 of 11
doi:10.1093/jxb/erm171

Journal of Experimental Botany
www.jxb.oxfordjournals.org

RESEARCH PAPER

A novel, non-invasive, online-monitoring, versatile and easy plant-based probe for measuring leaf water status

D. Zimmermann[1,*,†], R. Reuss[2,†], M. Westhoff[2,†], P. Geßner[2], W. Bauer[2], E. Bamberg[1], F-W. Bentrup[3] and U. Zimmermann[2]

Plant Biology ISSN 1435-8603

RESEARCH PAPER

Effects of environmental parameters and irrigation on the turgor pressure of banana plants measured using the non-invasive, online monitoring leaf patch clamp pressure probe

U. Zimmermann[1], S. Rüger[1], O. Shapira[2,3], M. Westhoff[1], L. H. Wegner[4], R. Reuss[1], P. Gessner[1], G. Zimmermann[1], Y. Israeli[5], A. Zhou[6], A. Schwartz[3], E. Bamberg[6,7] & D. Zimmermann[6,7]

Plant Biology ISSN 1435-8603

RESEARCH PAPER

A non-invasive probe for online-monitoring of turgor pressure changes under field conditions

M. Westhoff[1,*], R. Reuss[1,*], D. Zimmermann[2,*], Y. Netzer[3], A. Gessner[1], P. Geßner[1], G. Zimmermann[1], L. H. Wegner[4], E. Bamberg[2], A. Schwartz[3] & U. Zimmermann[1]

Agricultural Water Management 98 (2010) 124–133

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Whole-tree water balance and indicators for short-term drought stress in non-bearing 'Barnea' olives

Alon Ben-Gal[a,*], Dilia Kool[b], Nurit Agam[a], Gerardo E. van Halsema[b], Uri Yermiyahu[a], Ariel Yafe[a], Eugene Presnov[a], Ran Erel[a], Ahmed Majdop[a], Isaac Zipori[c], Eran Segal[a], Simon Rüger[d], Ulrich Zimmermann[d], Yafit Cohen[e], Victor Alchanatis[e], Arnon Dag[c]

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SI from plant-based measurements

Agricultural Water Management 142 (2014) 99–109

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Review

Plant-based sensing to monitor water stress: Applicability to commercial orchards

J.E. Fernández*

Irrigation and Crop Ecophysiology Group, Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC), Avenida de Reina Mercedes, n.° 10, 41012 Seville, Spain

In: Water Scarcity and Sustainable Agriculture in Semiarid Environment. Tools, Strategies, and Challenges for Woody Crops.
Eds.: I.F. García-Tejero and V.H. Duran-Zuazo
Academic Press, Elsevier 2018

Horticulturae **2017**, *3*, 35; doi:10.3390/horticulturae3020035

horticulturae

MDPI

Review

Plant-Based Methods for Irrigation Scheduling of Woody Crops

José Enrique Fernández

Group on Irrigation and Crop Ecophysiology, Instituto de Recursos Naturales y Agrobiología (IRNAS, CSIC), Avenida de Reina Mercedes, 10, 41012 Sevilla, Spain; jefer@irnase.csic.es

CHAPTER 9

Precision Irrigation in Olive (*Olea europaea* L.) Tree Orchards

José E. Fernández[1], Antonio Diaz-Espejo[1], Rafael Romero[1], Virginia Hernandez-Santana[1], José M. García[2], Carmen M. Padilla-Díaz[1], María V. Cuevas[1]

[1]Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC), Seville, Spain;
[2]Instituto de la Grasa (IG, CSIC) Campus Universidad Pablo de Olavide, Seville, Spain

SI from TDV, SF and TP measurements







PROS:

- Continuous & automatic data recording
- Sensors implemented with data transmission systems

CONS:

- Expensive
- Training is required for both installation and maintenance
- Heavy data processing
- Data interpretation is demanding

Suitable for specialized companies that deliver irrigation advice to the growers for a fee.

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Irrigation scheduling

1. The context

2. Methods to schedule irrigation

3. Scheduling irrigation in practice

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IS from automated plant-based measurements

Sap flow, trunk diameter variations and leaf turgor pressure have been widely tested.







- The plant is used as a biosensor

Required for PI
- Continuos and automatic data recording
- Sensors are implemented with data transmission systems

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IS from automated plant-based measurements



Agricultural Water Management 142 (2014) 99–109

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Plant-based sensing to monitor water stress: Applicability to commercial orchards

J.E. Fernández *

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Table 1
Requirements for a water stress indicator to be used in commercial orchards.

The sensors are related equipment (the system) must be inexpensive and easy to install, operate and maintain.
The system must be reliable and robust, capable of working under field conditions for the whole irrigation season.
The system must allow for automated and continuous data collection and data transmission, with low power requirements (batteries fed with solar panels).
The water stress index derived from the collected records must be highly sensitive, i.e. it must show a high signal:noise ratio.
The derived index must also show an early response to the onset of water stress.
The derived index must be related to a variable of economic importance, such as crop yield and fruit quality.
The derived index, or the sensor outputs in case they are used without any further data processing, must be easy to interpret.
If the index or outputs are not easy to interpret, the system must be provided with an application for visual readouts, graphs, historical records, and other tools to facilitate data interpretation.
The system should be easily implemented with an application for the combined use of the chosen index with a weather prediction system. This will improve the user capacity for adjusting the timing and intensity of irrigation under changing weather conditions.
The system should be easily combined with methods to define areas with characteristic water-stress behaviour within the orchard, such as remote imagery. This allows for precise irrigation in large, highly variable orchards.
The index must be suitable for automatic irrigation scheduling and control. In this case, the system should be implemented with expert systems, alarms, and other tools for an early detection and lower impact of malfunctions.

Reducing the complexity: 1. Hiring a specialized company



The grower can hire the services of a private company, which installs and maintains the sensors and related equipment, and process the data.

www.Verdtech.es
www.Phytech.com
www.Yara zim-plant-technology.com

The company sends instructions to the grower trough his/her mobile phone, for an easy scheduling of irrigation.

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Reducing the complexity: 1. Hiring a specialized company





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Reducing the complexity: 1. Hiring a specialized company



Sensor

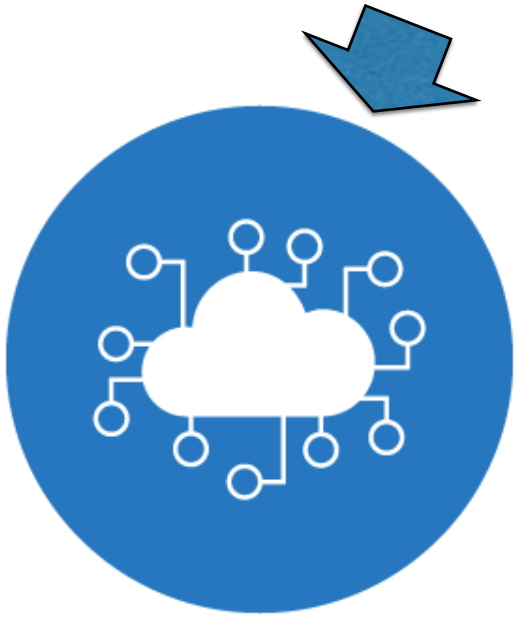


Transmitter



Gateway

weather forecast,
irrigation strategy



Cloud



App

The greater difficulty is here

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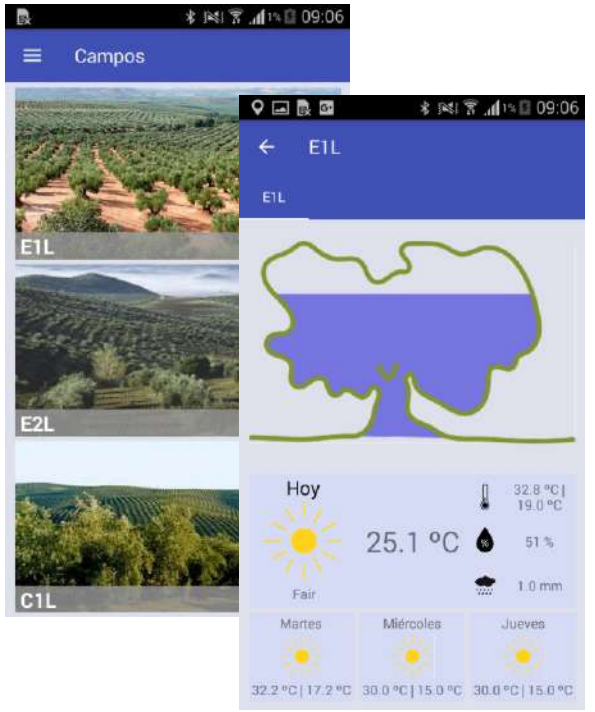
Reducing the complexity: 2. Advances on data processing



The Cloud

1. Meaning of the outputs
2. Real time processing

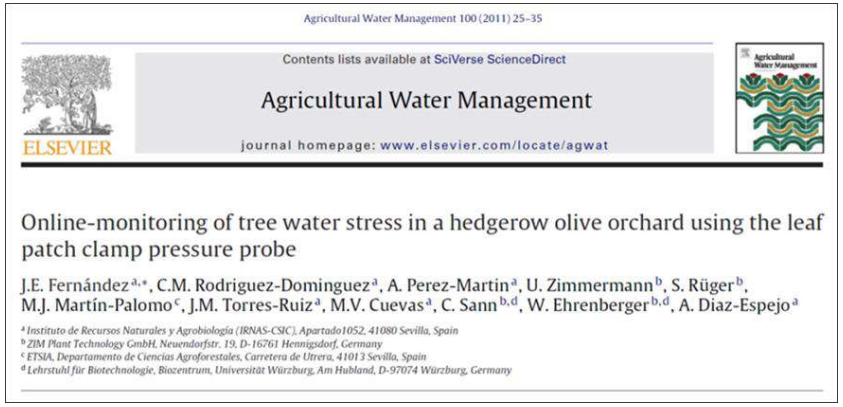
We can use *AI* techniques to process the data



App

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Reducing the complexity: 2. Advances on data processing



Agricultural Water Management 100 (2011) 25–35

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

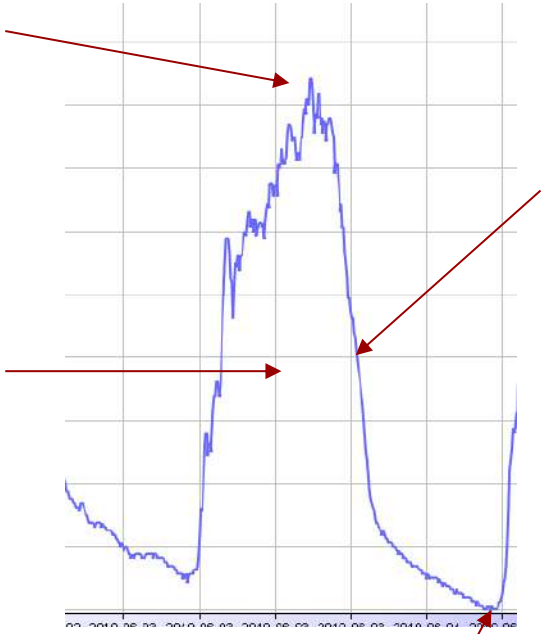
journal homepage: www.elsevier.com/locate/agwat

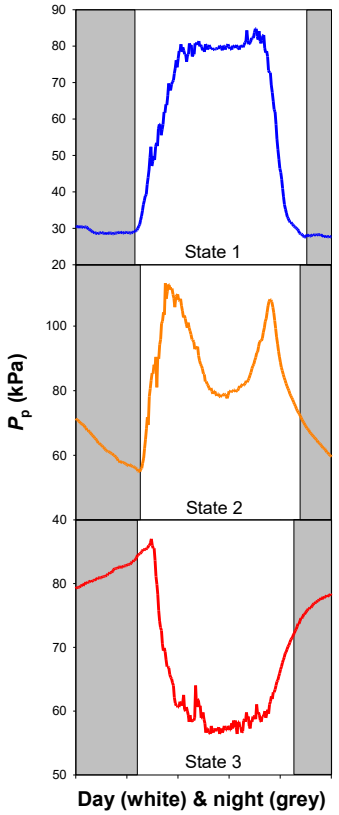
Online-monitoring of tree water stress in a hedgerow olive orchard using the leaf patch clamp pressure probe

J.E. Fernández[a,*], C.M. Rodriguez-Dominguez[a], A. Perez-Martin[a], U. Zimmermann[b], S. Rüger[b], M.J. Martín-Palomo[c], J.M. Torres-Ruiz[a], M.V. Cuevas[a], C. Sann[b,d], W. Ehrenberger[b,d], A. Diaz-Espejo[a]

[a] Instituto de Recursos Naturales y Agrobiología (IRNAS-CSIC), Apartado1052, 41080 Sevilla, Spain
[b] ZIM Plant Technology GmbH, Neuendorfstr. 19, D- 16761 Hennigsdorf, Germany
[c] ETSIA, Departamento de Ciencias Agroforestales, Carretera de Utrera, 4101 3 Sevilla, Spain
[d] Lehrstuhl für Biotechnologie, Biozentrum, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany











ψ_{stem} > -1.2 MPa **low stress**

-1.2 MPa > ψ_{stem} > -1.7 MPa **moderate stress**

ψ_{stem} < -1.7 MPa **severe stress**

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Reducing the complexity: 2. Advances on data processing

Computers and Electronics in Agriculture 142 (2017) 181–189

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Classification models for automatic identification of daily states from leaf turgor related measurements in olive

Rafael Dreux Miranda Fernandes [a,*], Maria Victoria Cuevas [a], Virginia Hernandez-Santana [a], Celia M. Rodriguez-Dominguez [b], Carmen M. Padilla-Díaz [a], José Enrique Fernández [a]

[a] Irrigation and Crop Ecophysiology Group, Instituto de Recursos Naturales y Agrobiología (IRNAS, CSIC), Avenida Reina Mercedes, 10, 41012- Seville, Spain
[b] School of Biological Sciences, University of Tasmania, Private Bag 55, Hobart, Tasmania 7001, Australia

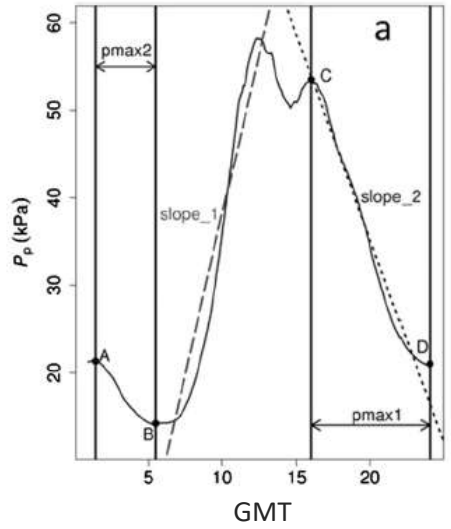
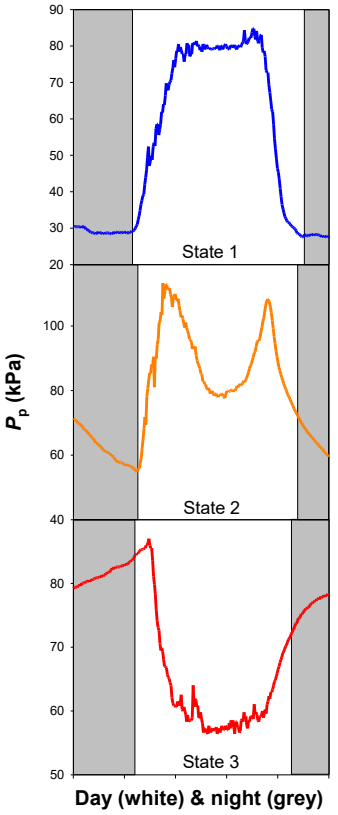


Table 3
Confusion matrix and overall accuracy for the rf2 model. The II.1 to II.3 groups are the groups in which the state II curves were split to obtain the model. A total of 44 curves were considered in the analysis. Data in the table show the number of curves in which the group determined according to the Ψ_{stem} and g_s values (Reference) agreed with the group predicted by the model (Prediction), as well as the number of curves in disagreement between Reference and Prediction.

Prediction	Reference		
	II.1	II.2	II.3
II.1	17	2	0
II.2	0	14	1
II.3	0	2	8
Accuracy	100%	77.8%	88.9%



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Reducing the complexity: 2. Advances on data processing



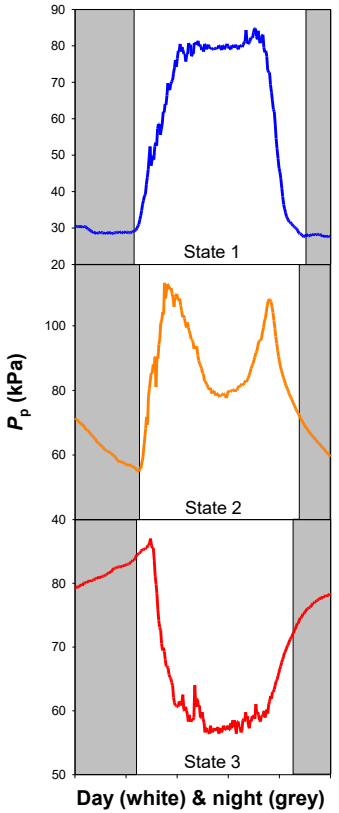


Dr. David Muñoz

TEP 950 Research Group

Estimation, prediction, optimization and control

Dep. of Systems Engineering and Automation





ψ_{stem} > -1.2 MPa **low stress**

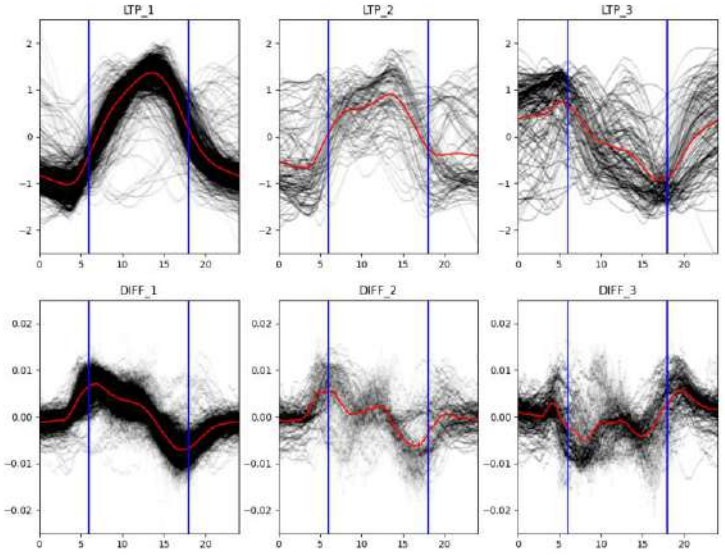
-1.2 MPa > ψ_{stem} > -1.7 MPa **moderate stress**

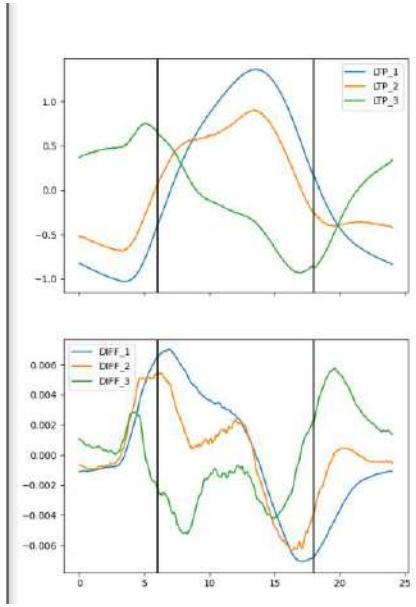
ψ_{stem} < -1.7 MPa **severe stress**

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Reducing the complexity: 2. Advances on data processing

Stress level classifier based on linear discriminant (LDA)
and principal component (PCA+LDA) of daily LTP and meteorological readings.





Real Vs Estimated	Mild %	Moderate %	Severe %
Mild	91	7	2
Moderate	44	30	25
Severe	4	10	87

Data from experiments on efficient irrigation strategies carried out in 2014, 2015, 2016 and 2019. Training carried out with 2014 data, validation carried out with the rest.

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Reducing the cost: 1. Considering the AMUs

Great reductions on the monitoring costs can be achieved by installing the sensors and related equipments in the defined AMUs.



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Reducing the cost: 2. Cheaper sensors



vs.



- High Precision
- High costs
- Limited number of stations

- Low cost
- Network of hundreds of biohybrid stations
- High risk / high gain

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Reducing the cost: 2. Cheaper sensors



BOSCH

Invented for life



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Reducing the cost: 2. Cheaper sensors





Evaluation of the BOSCH system by the ECOVER Group (2016-2020)

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Other improvements: 1. New sensors

Dr. Díaz-Espejo



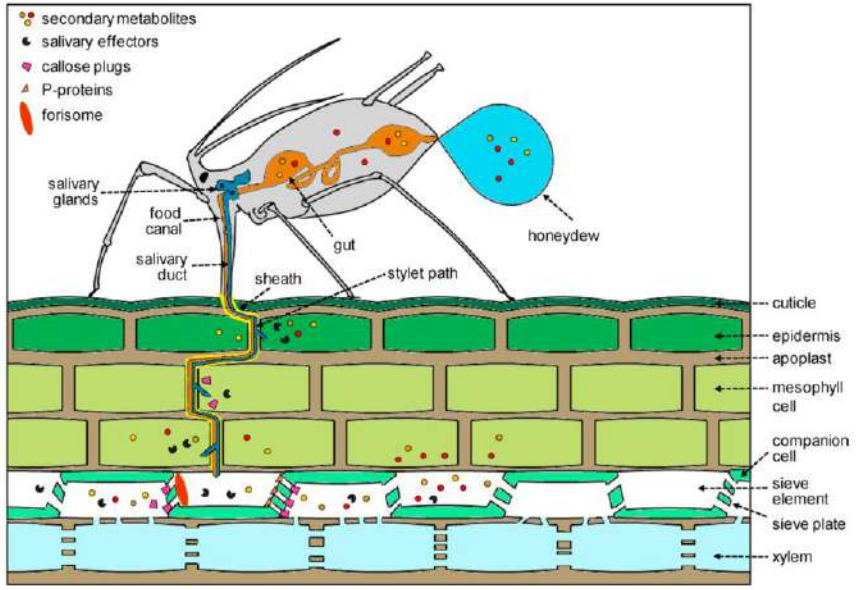
WATCHPLANT

WATCHPLANT
SMART BIOHYBRID PHYTO-ORGANISMS FOR ENVIRONMENTAL IN SITU MONITORING

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

H2020-FETPROACT-2020

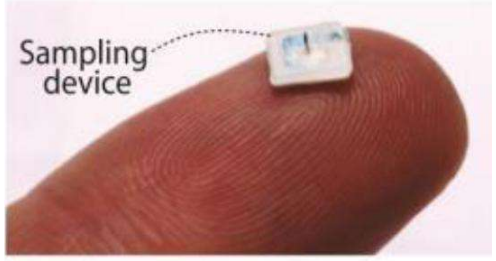




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Other improvements: 1. New sensors



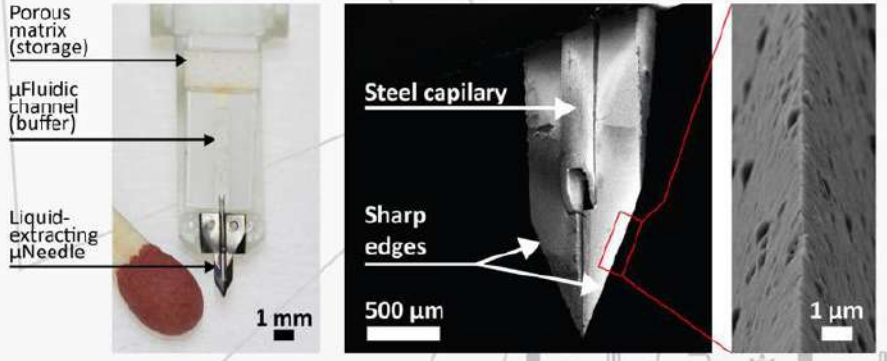


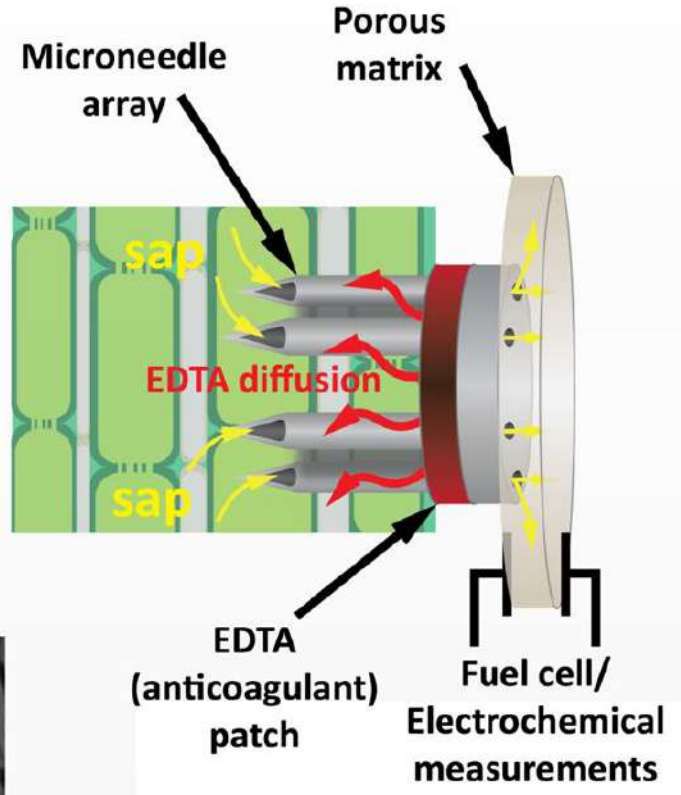
ABA monitoring

Plant tissue mechanics
- Required material strength
- Required sharpness

Plant physiology
- Sap coagulation
- Anticoagulant delivery

Microfluidics
- Sap viscosity, supply rate
- Sap transport inside the device

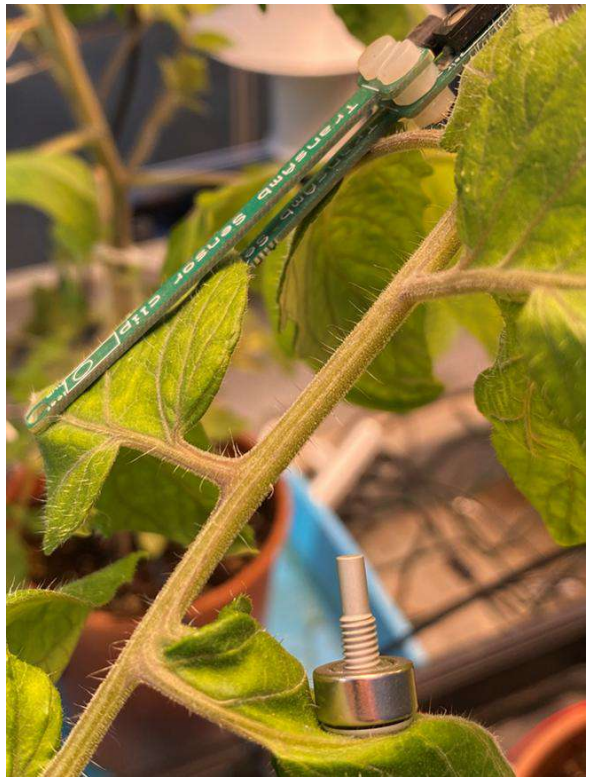


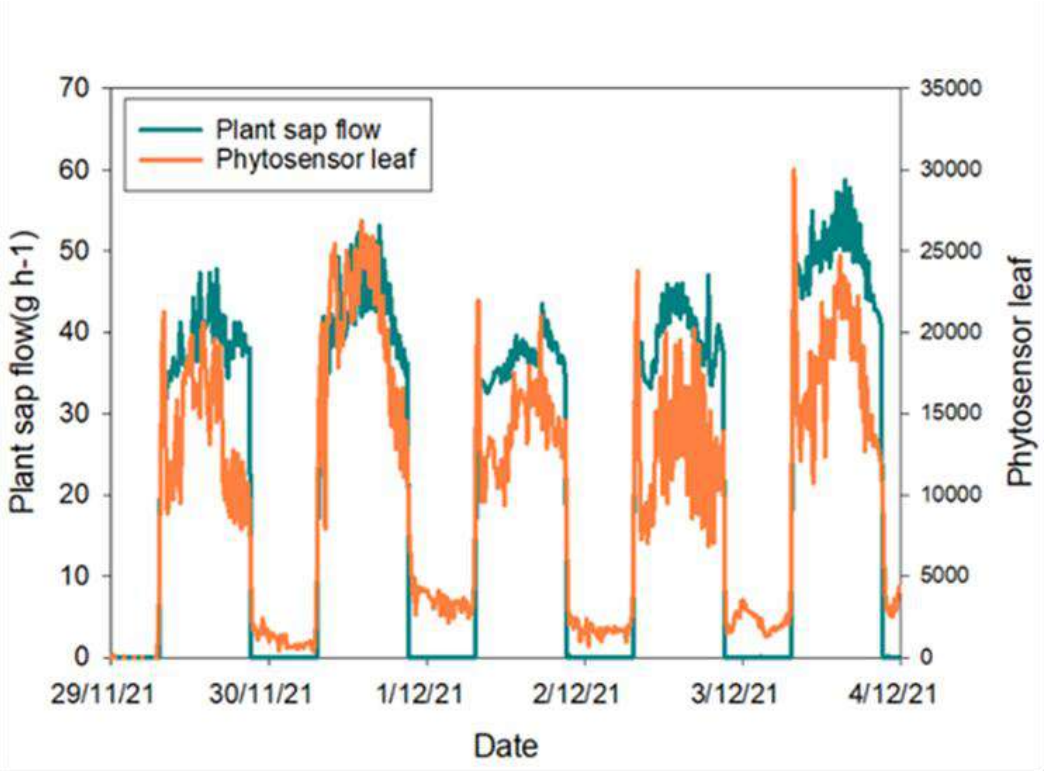


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Other improvements: 1. New sensors

Transpiration sensor





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Other improvements: 1. New sensors

PSY1 Stem Psychrometer (ICT Int.)



Florapulse microtensiometer



FloraPulse : the most accurate irrigation guidance for orchards and vineyards

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Other improvements: 2. New methods





Agricultural and Forest Meteorology 218–219 (2016) 92–101

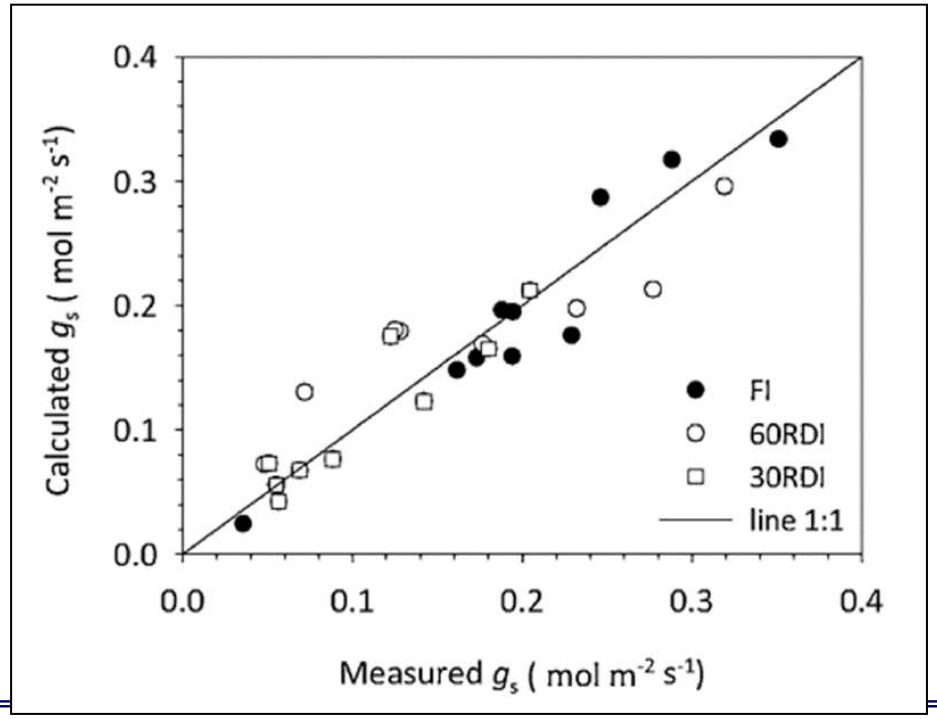
Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit

V. Hernandez-Santana [a], J.E. Fernández [a], C.M. Rodriguez-Dominguez [a,b], R. Romero [a], A. Diaz-Espejo [a,*]





$g_s \approx J_s / D_a$

Enrique Fernández
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Other improvements: 2. New methods

Dr. Hernandez-Santana



Physiological basis for the application of deficit irrigation in digital orchards
(2022-2023)

MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

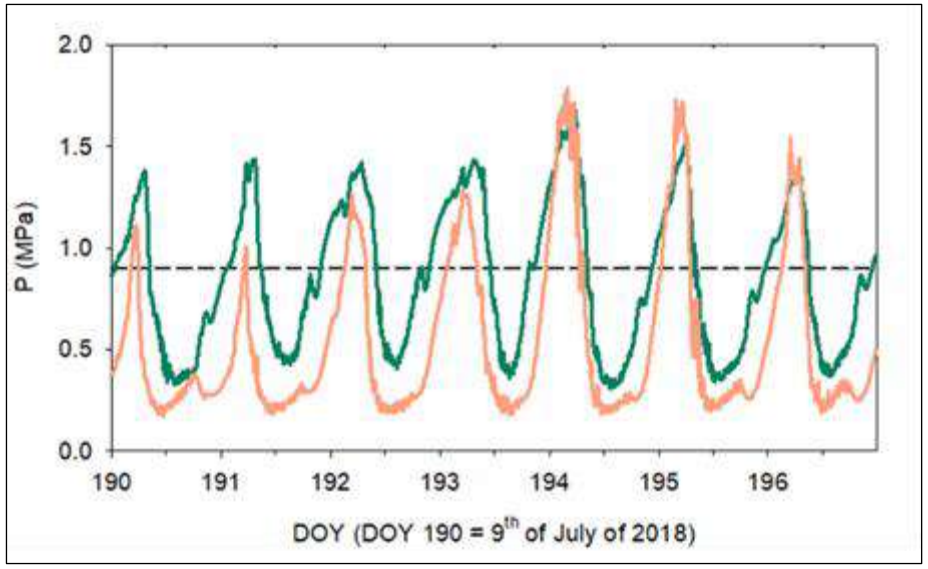
FruitCREWS

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY





Coussement et al., (2021)
Hernandez-Santana et al., (2021)



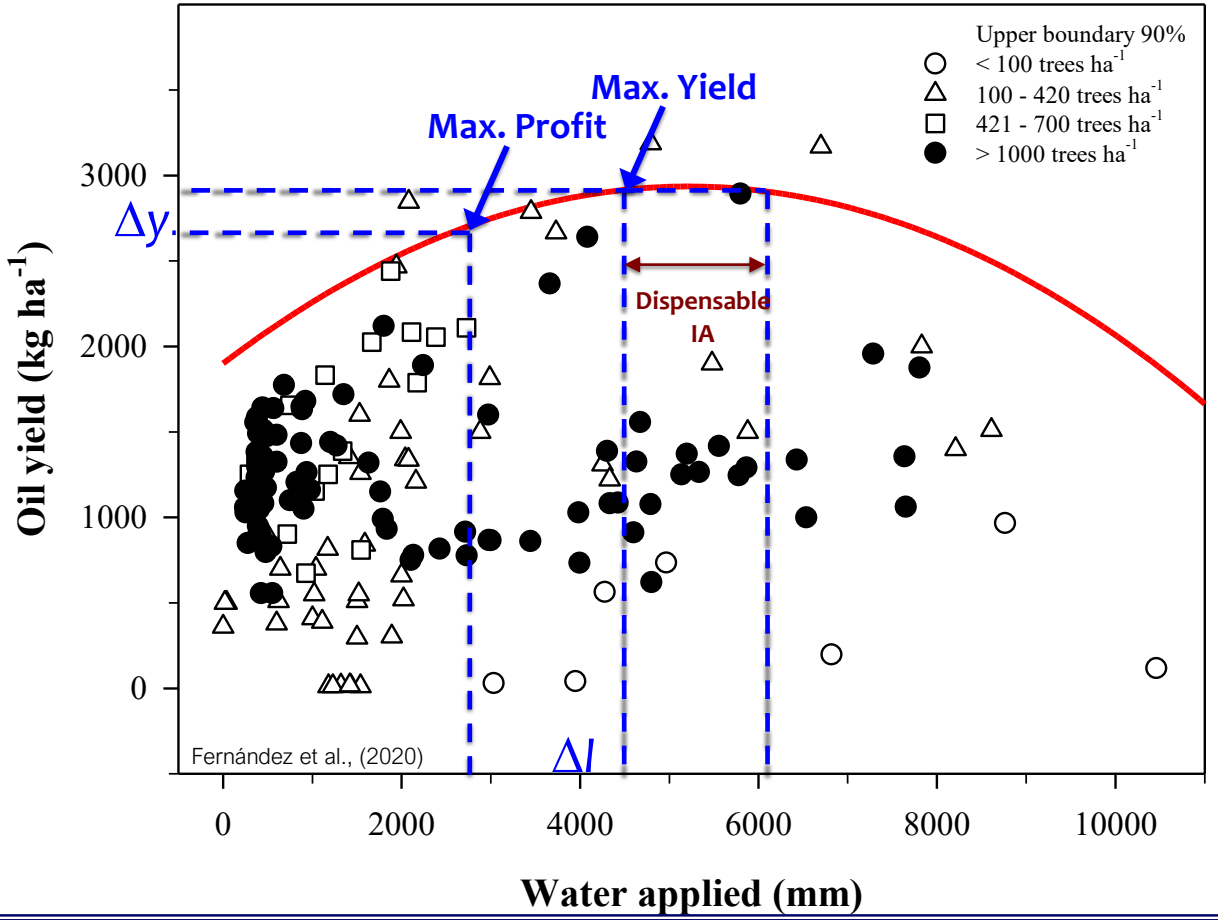
Enrique Fernández
jefer@irnase.csic.es

Other improvements: 3. Modelling

We are working on a model to schedule irrigation from simulated values of stomatal conductance.

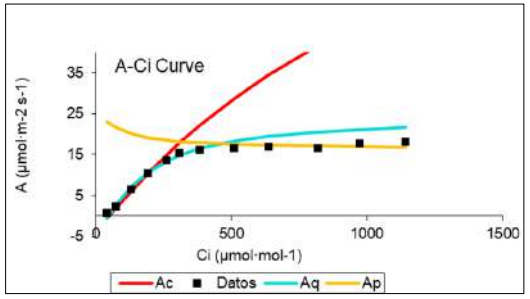
Dr. Díaz-Espejo



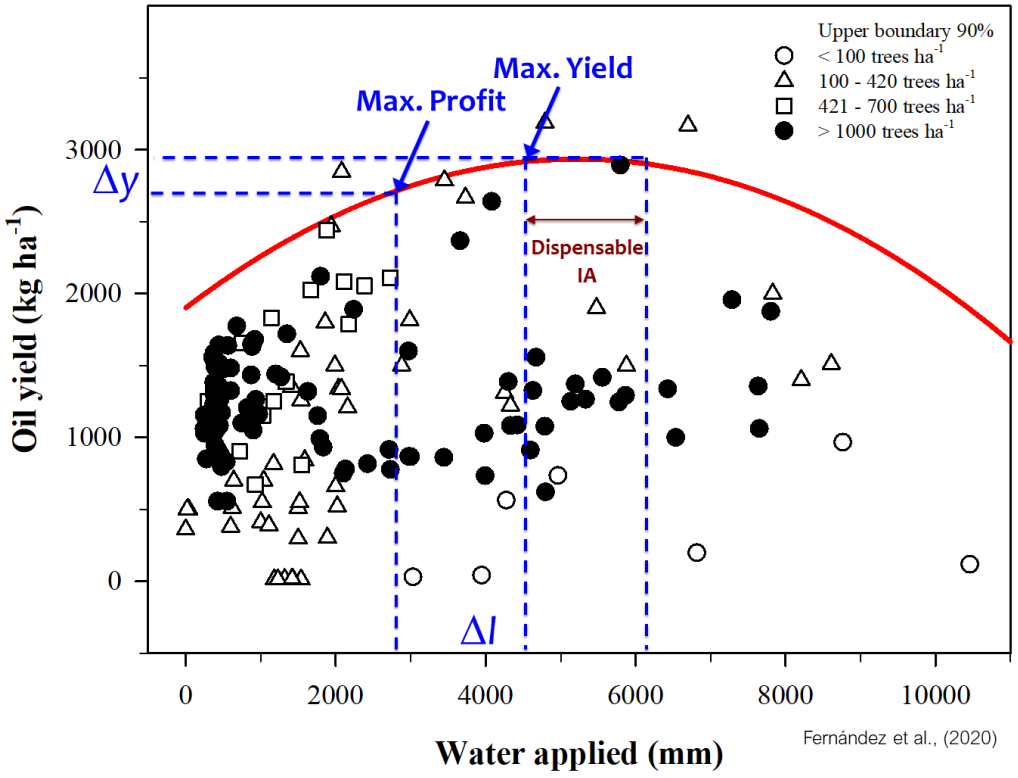


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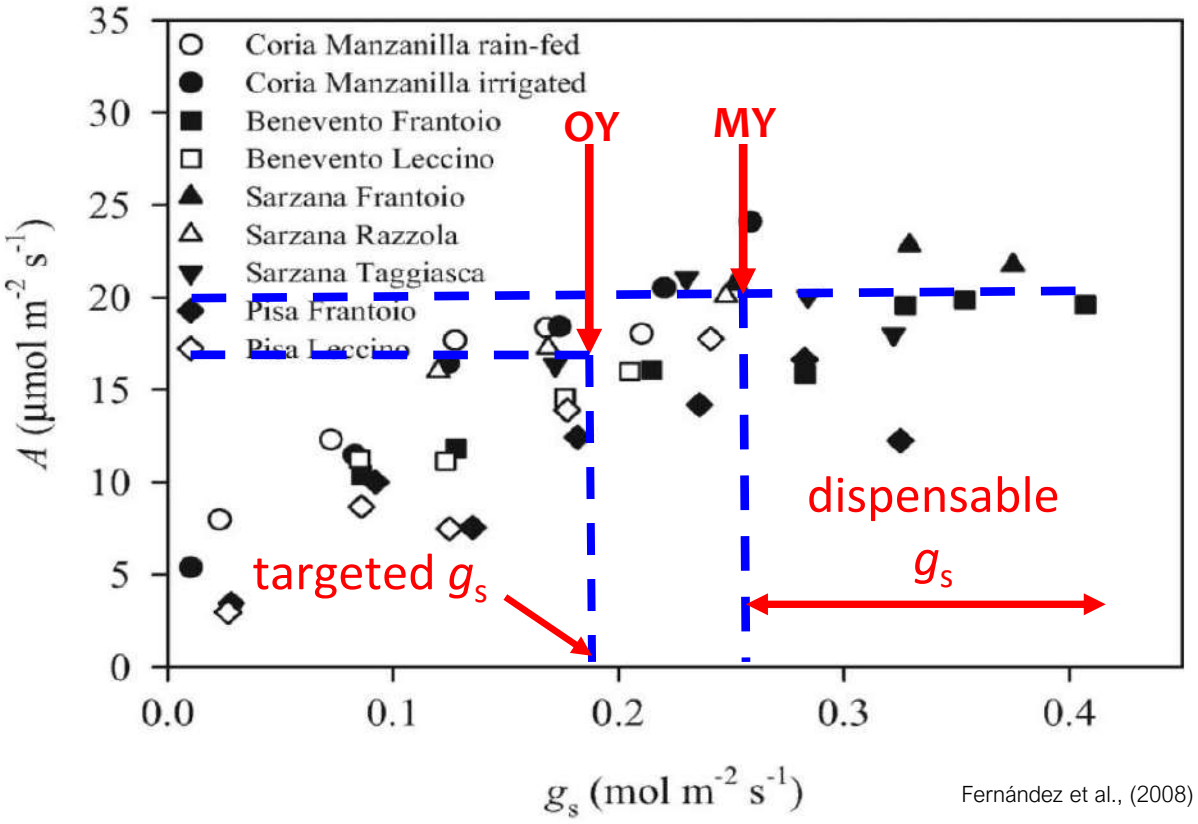
Other improvements: 3. Modelling



The A_N-g_s relationship can be used as a proxy of the yield-water used relationship.



Fernández et al., (2020)



Fernández et al., (2008)

Enrique Fernández
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Other improvements: 3. Modelling

Dr. V. Hernandez-Santana





$$g_s \approx J_s / D_a$$



Agricultural and Forest Meteorology 218–219 (2016) 92–101

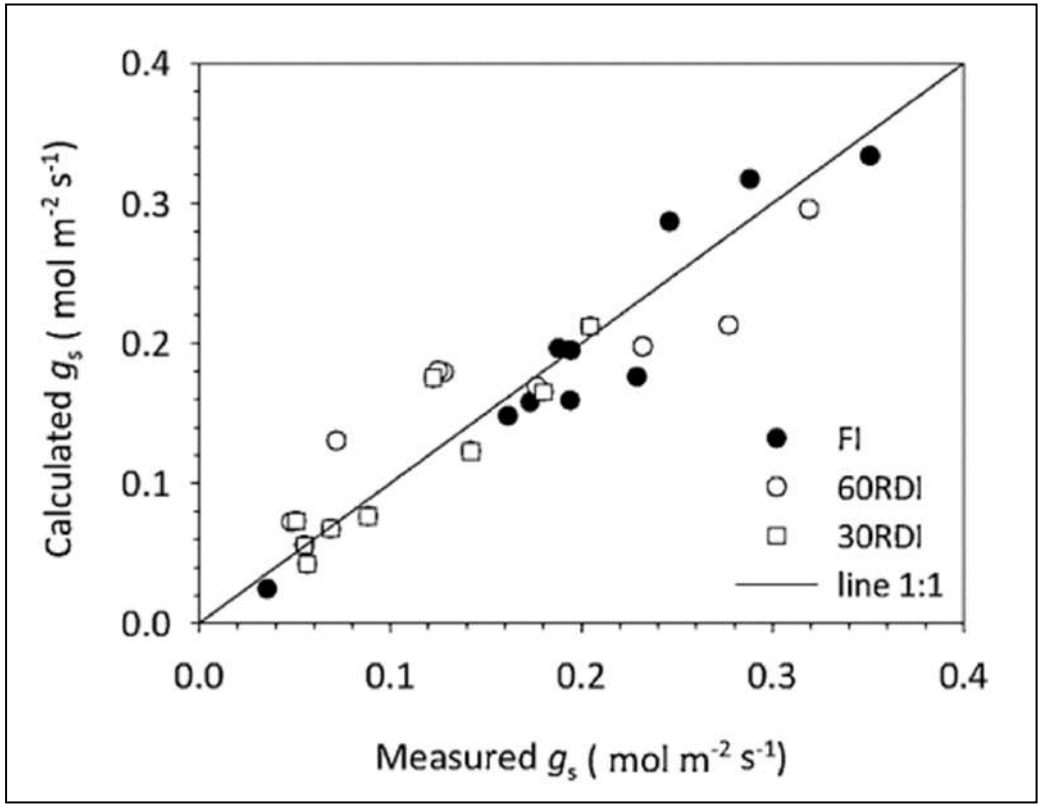
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The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit

V. Hernandez-Santana[a], J.E. Fernández[a], C.M. Rodriguez-Dominguez[a,b], R. Romero[a], A. Diaz-Espejo[a,*]

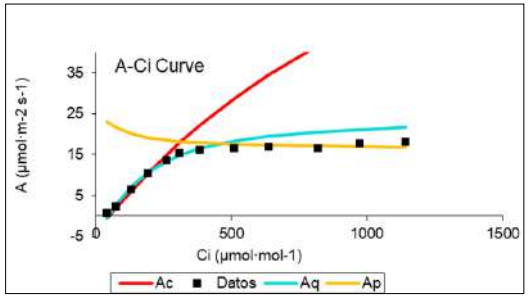


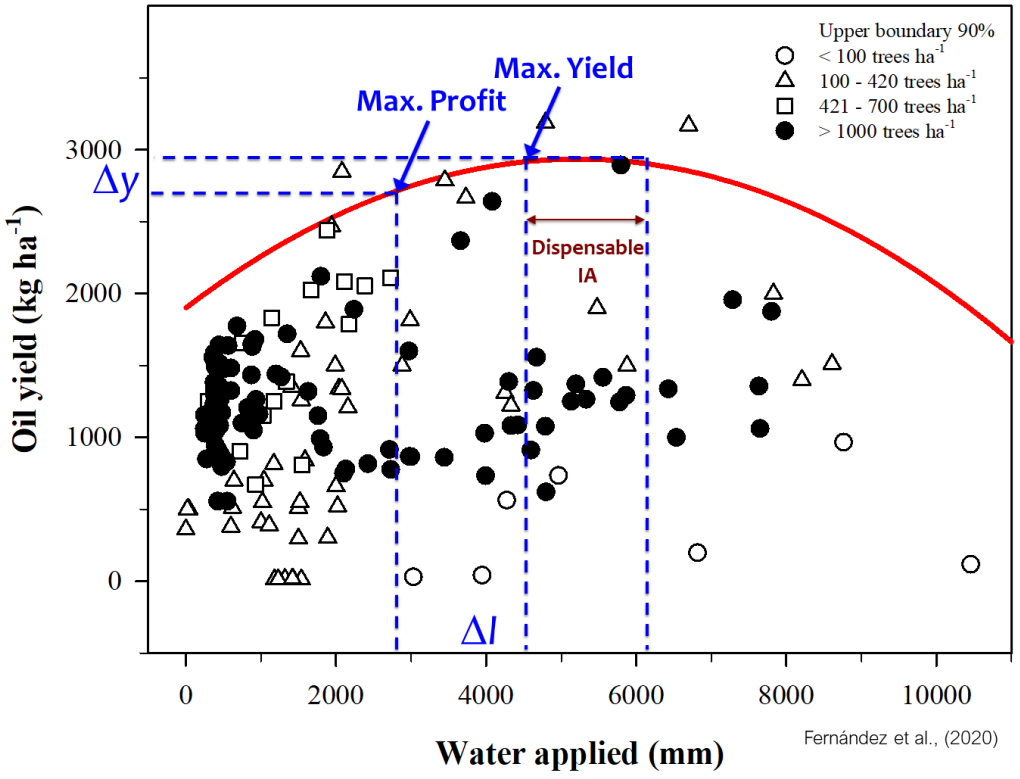
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Other improvements: 3. Modelling

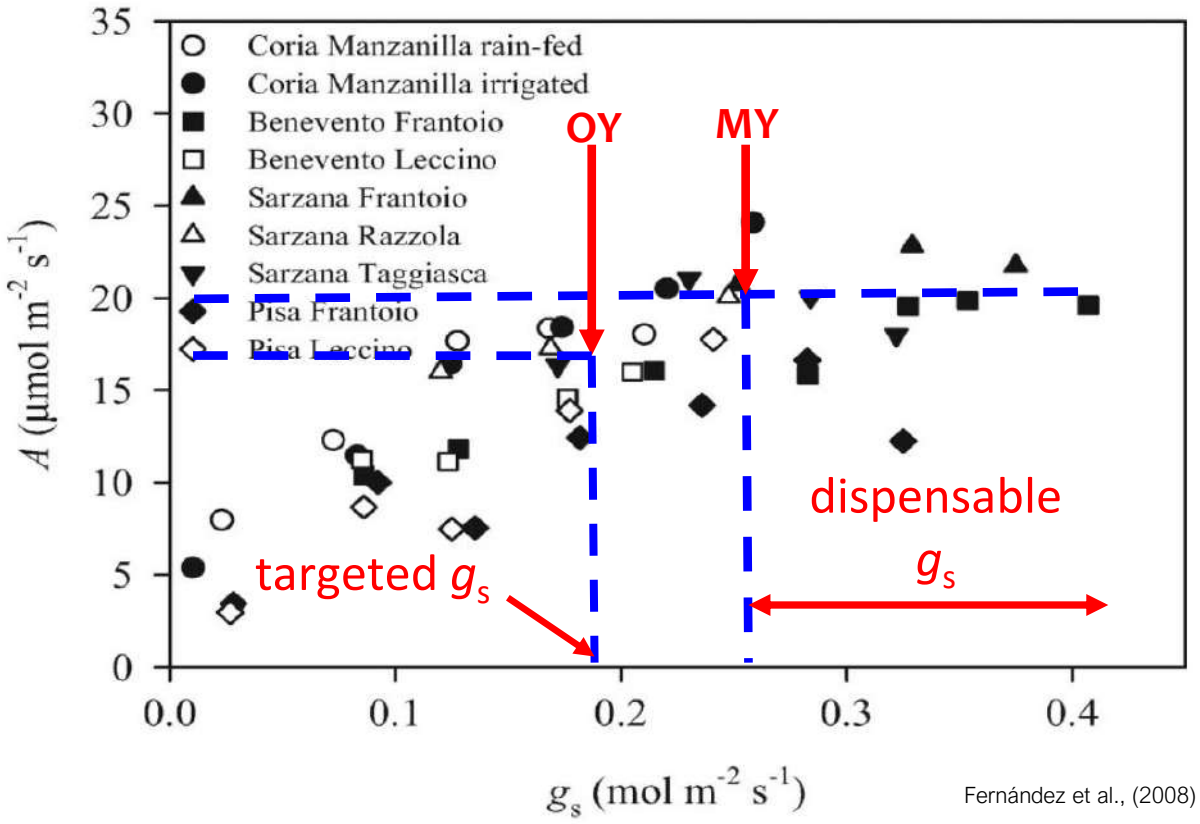


But the assimilated carbon can go
to different organs, not only to the fruits.





Fernández et al., (2020)



Fernández et al., (2008)

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Other improvements: 3. Modelling

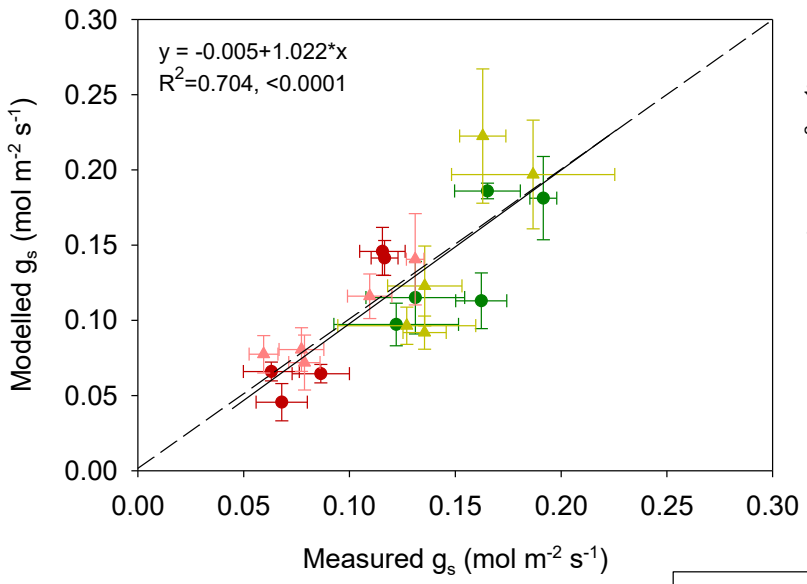
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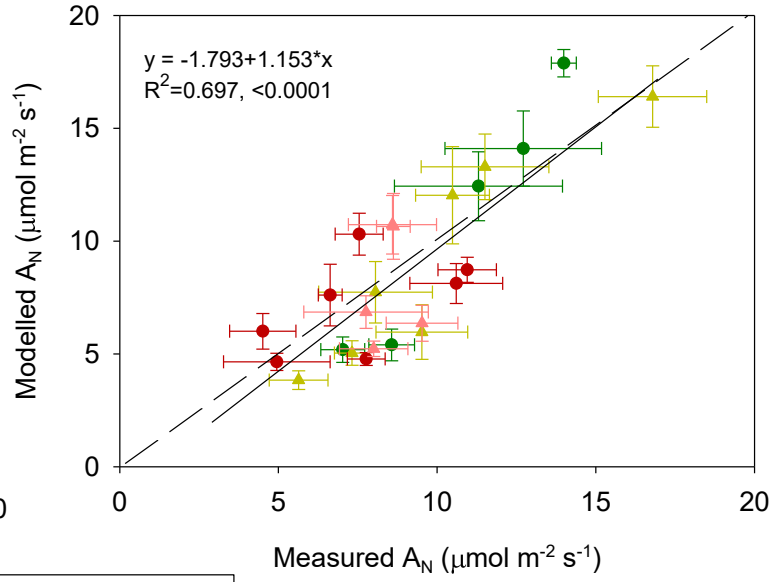
Agricultural and Forest Meteorology

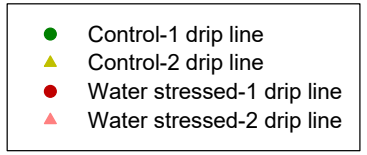
journal homepage: www.elsevier.com/locate/agrformet

Relationships between fruit growth and oil accumulation with simulated seasonal dynamics of leaf gas exchange in the olive tree

V. Hernandez-Santana[a], R.D.M. Fernandes[a], A. Perez-Arcoiza[a], J.E. Fernández[a], J.M. Garcia[b], A. Diaz-Espejo[a,*]







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Other improvements: 3. Modelling

J_s / D → *Used to infer* → g_s → *Allowed us to model* → A_N

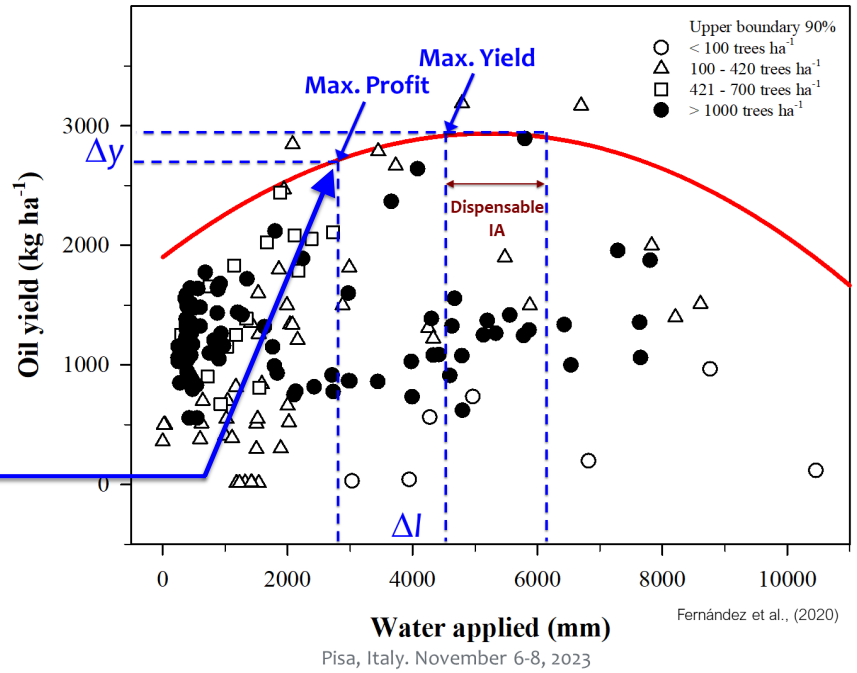
A_N → *Well watered conditions* → **Fruit growth**, **Vegetative growth**

A_N → *Water stressed conditions* → **Fruit growth**

We can adjust irrigation at real time, to get the A_N level that better matches our production target.

In other words:

We have now a method to adjust irrigation for this point to be in the position of the curve that better matches our production target.



Fernández et al., (2020)

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Other improvements: 4. Decision support systems



ISADORA PROJECT

MINISTERIO DE CIENCIA E INNOVACIÓN

UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
"Una manera de hacer Europa"

AGENCIA ESTATAL DE INVESTIGACIÓN

SOFTWARE TOOL TO SCHEDULE IRRIGATION

Approach	*Output*
1. The A&P Method	→ ET_c
2. The Mechanistic Model	→ Targeted g_s
3. TDV or LTP readings + MACHINE LEARNING	→ WSI

+

- 3-days weather forecast
- Leaf area (except for A1)
- Soil evaporation model (for A2 only)
- Phenological stage
- Irrigation strategy
- Stress level from RI

→



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Is all this enough?

Advances on sensoring + digitalisation + AI
open new ways to optimize water use in agriculture





	Years in the market
Sap flow	40
Trunk dimeter	30
Leaf turgor pressure	12

¿Which is the percentage of orchards/farms irrigated with those systems? < 5%

¿And with conventional systems (K_c method, soil water measurements…)? < 30%

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Socio-economic aspects



- Many rural areas do no have access to the internet.

- Low innovation capacity, due to a low capacity for investment.

- The average age of growers is high.

  - In Andalusia, 25 % of the growers are 65 year-old, or more;
    63 % between 41 and 65 years of age;
    12 % only are below 40 years of age.

    Consejería de Agricultura, Pesca y Desarrollo Sostenible de la Junta de Andalucía, 2019

A new generation may be required for a complete adoption of digital agriculture

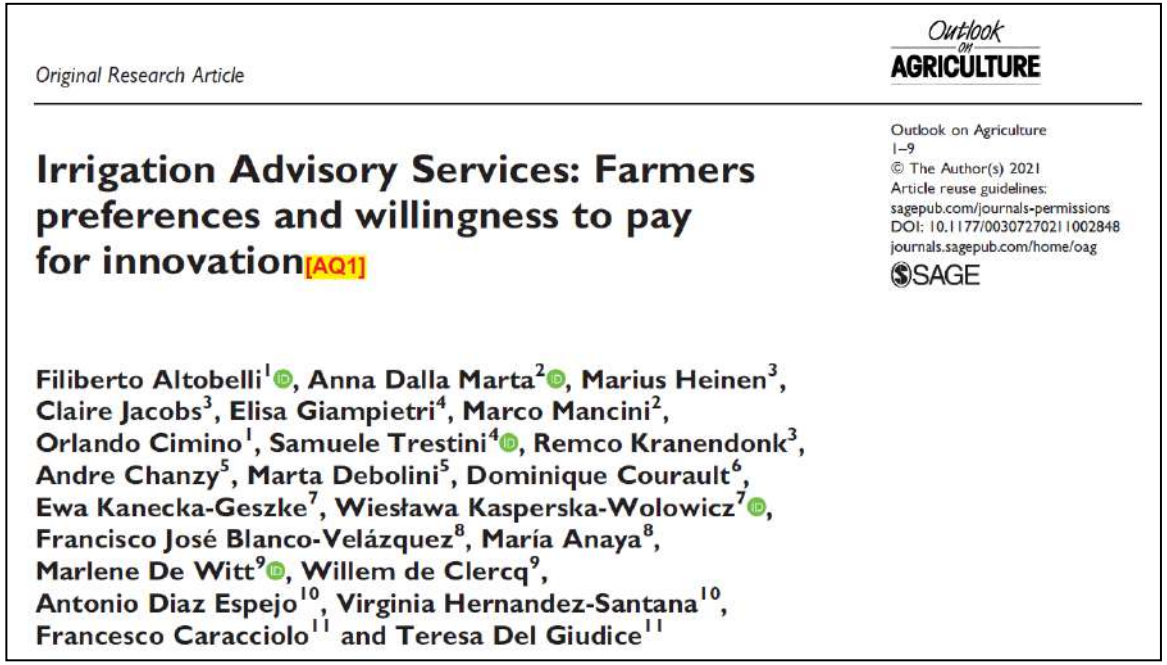
- The grower is not convinced on the benefits of the new approach.

  - Companies providing sensors/support should inform the grower on the profitability of the system/approach they sell.

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Socio-economic aspects

A survey on the individual risk attitude of growers from Spain, The Netherlands, Italy, Poland and South Africa.



Original Research Article

Outlook on AGRICULTURE

Irrigation Advisory Services: Farmers preferences and willingness to pay for innovation[AQ1]

Outlook on Agriculture
1–9
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Filiberto Altobelli[1], Anna Dalla Marta[2], Marius Heinen[3], Claire Jacobs[3], Elisa Giampietri[4], Marco Mancini[2], Orlando Cimino[1], Samuele Trestini[4], Remco Kranendonk[3], Andre Chanzy[5], Marta Debolini[5], Dominique Courault[6], Ewa Kanecka-Geszke[7], Wiesława Kasperska-Wolowicz[7], Francisco José Blanco-Velázquez[8], María Anaya[8], Marlene De Witt[9], Willem de Clercq[9], Antonio Diaz Espejo[10], Virginia Hernandez-Santana[10], Francesco Caracciolo[11] and Teresa Del Giudice[11]

"Farmers are actually willing to pay to introduce an irrigation support system that translates into an economic advantage over their current situation."

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The Ecophyisiology and Crop Irrigation (ECOVER) group

Institute for Natural Resources and Agrobiology (IRNAS)
Spanish National Research Council (CSIC)

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Perspectives on the use of water in agriculture



J.E. (Enrique) Fernández

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Plant Ecophysiology and Irrigation group
Spanish National Research Council (CSIC)

The problem

- 70 % of water withdrawals are per agricultural use (over 80 % in arid areas)
- 11 % of the world's land surface is cultivated (1600 Mha, 20 % irrigated)
- Food demand is expected to increase 60 % by 2050 (up to 100 % in developing countries)

1. There is a demand for improving productivity. How can we do it?

2. Many assume that high-tech irrigation will favor water saving. Is that true?

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The problem is not new

Three major advances to improve the use of water in agriculture.

Israel, 1950s



(1) Localized irrigation



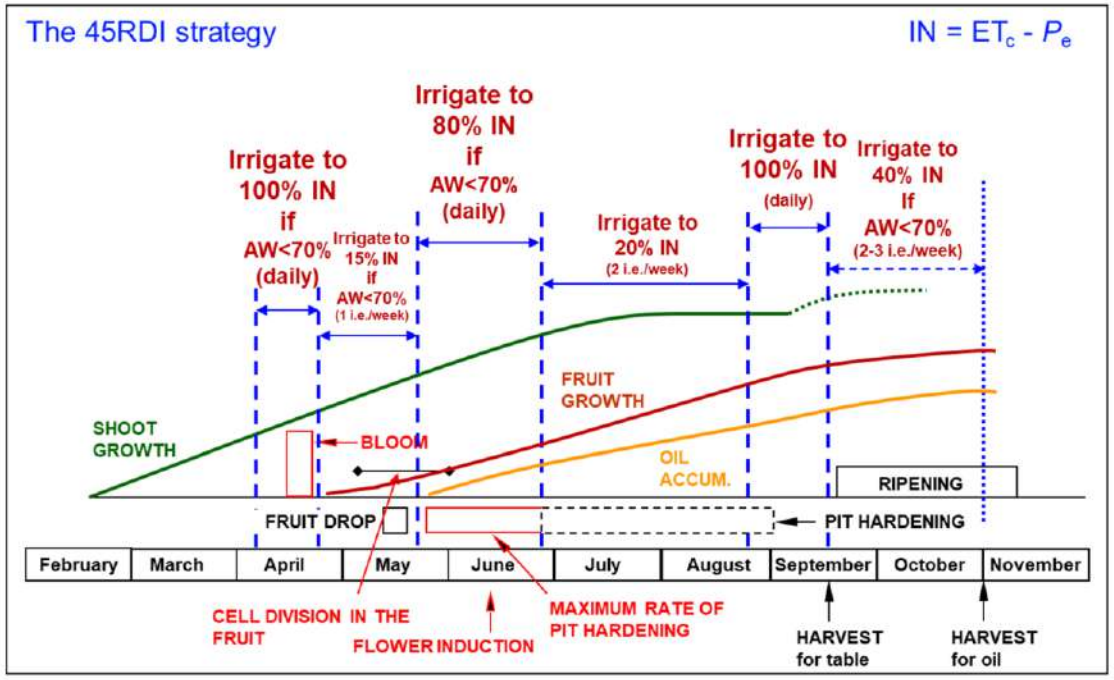
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The problem is not new

Three major advances to improve the use of water in agriculture.

(2) Deficit irrigation strategies

Semi-arid and arid countries, 1980s



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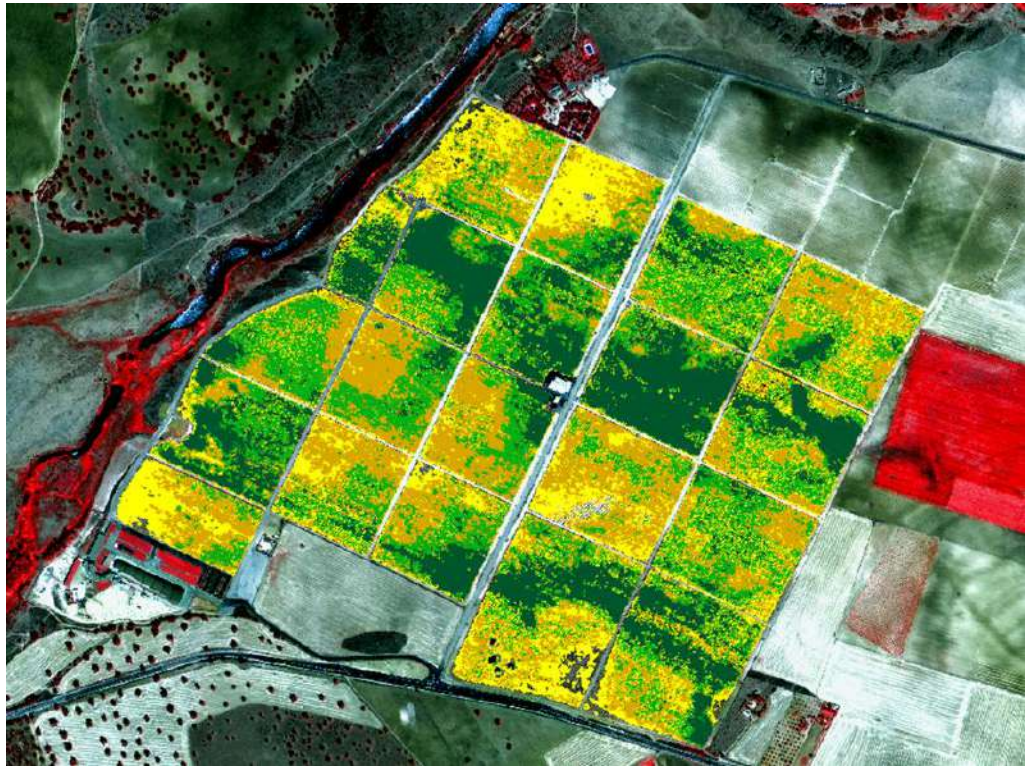
The problem is not new

Three major advances to improve the use of water in agriculture.

(3) Precision irrigation

Semi-arid and arid countries, 2000s

Implies digitalization (Agriculture 4.0-6.0)



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The problem is not new

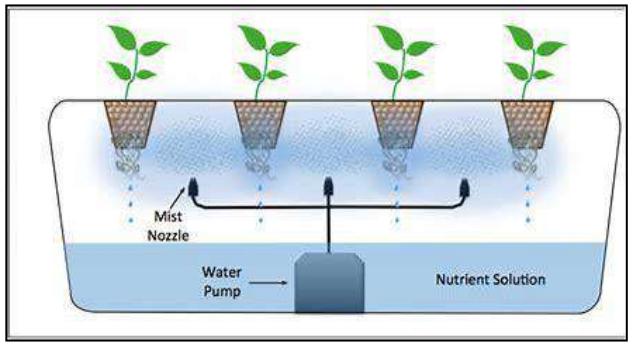
Recent advances

New practices & types of agriculture

Vertical Agriculture



Aeroponics



Genomics

Enhanced Breeding Programs: Genomics enables marker-assisted selection (MAS) and genomic selection (GS), which allow breeders to identify and select plants with desirable traits (e.g. disease resistance, drought tolerance, high yield) more accurately and efficiently. This reduces the time required to develop new crop varieties.

Genetic Modification and Gene Editing: Techniques like CRISPR-Cas9 allow precise modifications of crop genomes to introduce beneficial traits such as improved nutritional content, pest resistance

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The problem is not new

From Agriculture 4.0 to 6.0

Key Features of Agriculture 4.0:

1. Digital Tools: Use of Internet of Things (IoT), sensors, GPS, and drones to monitor and optimize farming practices.
2. Big Data: Data analytics to enhance decision-making, such as predicting weather patterns, pest outbreaks, or optimal planting times.
3. Automation: Precision agriculture technologies, including autonomous tractors and robotic harvesters.
4. Sustainability Focus: Efficient use of water, fertilizers, and pesticides to reduce waste and environmental impact.
5. Connectivity: Farm equipment and management systems linked through cloud computing and smart devices.

Key Features of Agriculture 6.0:

1. Sustainability at Core: Focus on achieving carbon-neutral or regenerative agricultural practices, with an emphasis on restoring ecosystems.
2. Integration with Society: Inclusion of social goals such as rural development, equitable resource distribution, and food security.
3. Circular Economy: Reducing waste through closed-loop systems, recycling nutrients, and integrating renewable energy sources.
4. Advanced Biotechnologies: Leveraging gene editing (e.g., CRISPR), synthetic biology, and microbiome engineering to improve crop resilience and yield.
5. Ethical AI: Use of artificial intelligence for predictive modeling, but with strong ethical frameworks to ensure fairness and privacy.

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Which kind of agriculture should be promoted?

1. Industrial Agriculture

2. Sustainable Agriculture

3. Organic Agriculture

4. Precision Agriculture

5. Agroforestry

Does the moon influence crop performance/quality?

- Its gravitatory force on you is 288,000 times lower than the one exerted by the Earth.
- Its light energy per unit of surface is 128,000 times lower than the solar light in a cloudy day, and 400,000 lower than the solar light in a sunny day.

6. Diversified Agriculture (encompasses the practice of growing multiple types of crops and raising various livestock on the same farm)

7. Permaculture (holistic approach that designs agricultural landscapes to mimic natural ecosystems, aiming for sustainability and self-sufficiency

8. Urban Agriculture

9. Regenerative Agriculture (focuses on restoring and enhancing the health of ecosystems, particularly soil health, by following practices that increase biodiversity and water retention)

10. Hydroponics and Aquaponics

11. Traditional and Subsistence Agriculture (practices that have been used for centuries, often involving small-scale farming aimed at self-sufficiency)

12. Biodynamic Agriculture (the farm is viewed as a self-sustaining organism, with a balance between crops, animals, soil, and biodiversity. They give relevance to the impact of the moon on crops)

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Which kind of agriculture should be promoted?

Sustainable intensive agriculture

Conventional agriculture



Food security is not ensured

Intensive agriculture



Combined with integrated crop management practices, and in the right areas, it could be a feasible solution

Diversified agriculture



Optimum (perhaps) but difficult to apply

Maximum output per unit of input

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Which kind of agriculture should be promoted?

PRIORITY: **Production** ⟷ **Reduced environmental impact**

Industrial agriculture
(Green Revolution)

Integrated farming
Organic farming

↑

Sustainable Intensive Agriculture (Tara Garnett, 2013)

- Fair profit to the grower
- Food security
- Respect to the environment: biodiversity & landscape
- Socio-economic welfare of the rural community

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Sustainable Intensification

The **sustainable intensification** approach uses technical&scientific advances to increase the productivity of every input used for crop production, at the same time that the environmental impact is reduced and the socio-economic conditions are improved.

It tries to ensure food security

Environmental policies are taken into account: subsidies are crucial

All agents are considered:

Producers – transformation&transport – sellers – consumers – environmental agencies - Administration

It improves the quality of life :

- Fair trade conditions for producers
- High-quality products for consumers at reasonable prices
- Better socio-economic conditions in rural areas

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Sustainable Intensification

Those goals require innovative approaches:

- High-tech irrigation is required (sensoring, digitalization, DSS, AI…)

- Deficit irrigation will be compulsory in most areas

- Use of genetically improved cultivars

- Redefinition of the production target

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The production target

Conventional p.t.: to obtain maximum yield

Rational p.t.: to optimize crop water productivity

WP_c = yield (kg ha^{-1}) / water used (m^3 ha^{-1})

Better p.t.: to increase economic crop water productivity and to ensure food security at the same time that the environmental impact is reduced

The challenge is to find the optimum equilibrium between these three requirements

- Maximum EWP_c = Profit (€ ha^{-1}) / water used (m^3 ha^{-1})
- Maximum yield per unit of soil
- Lower environmental impact

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Combining different approaches

Basic pillars

Innovative method based on stomatal conductance (g_s) and leaf area

Novel use of sensors



Use of GIS platforms already available, specific and functional

Farm heterogeneity and leaf area



Incorporation of low-cost sensors

To facilitate the implementation



SOURCE: Slide provided by Dr. Antonio Díaz-Espejo

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Digitalization favours effective data use

SAPFLUXNET

The collected data can feed databases for meta-analysis



Aims

- Understanding the carbon and water fluxes in the plant
- Building reliable, mechanistic models
- Identifying variations due to location, management, cultivars…

→ Reliable decision-making

SOURCE: Slide provided by Dr. Virginia Hernandez-Santana

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Do we have enough capacity to meet current challenges in irrigation?

- Scientific & Technical advances are enough to guarantee effective water stress monitoring and irrigation scheduling: Science & Technology are not limiting factors.

- Still, the growers' willingness to adopt high-tech solutions is low. ¿How to address this?

  - Avoid black-box approaches: growers like to have control

  - Better if the monitored variable is clearly related to a variable of economic importance, such as crop yield or yield quality

  - The new technology must be easy to use

  - The new technology must prove profitable

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The economic factor

The Sanabria orchard



1667 'Arbequina' trees ha^{-1}

Orchard (SDI)	70 % IN
100 % ET_c	100 % IN
60RDI	60 % IN
30RDI	30% IN

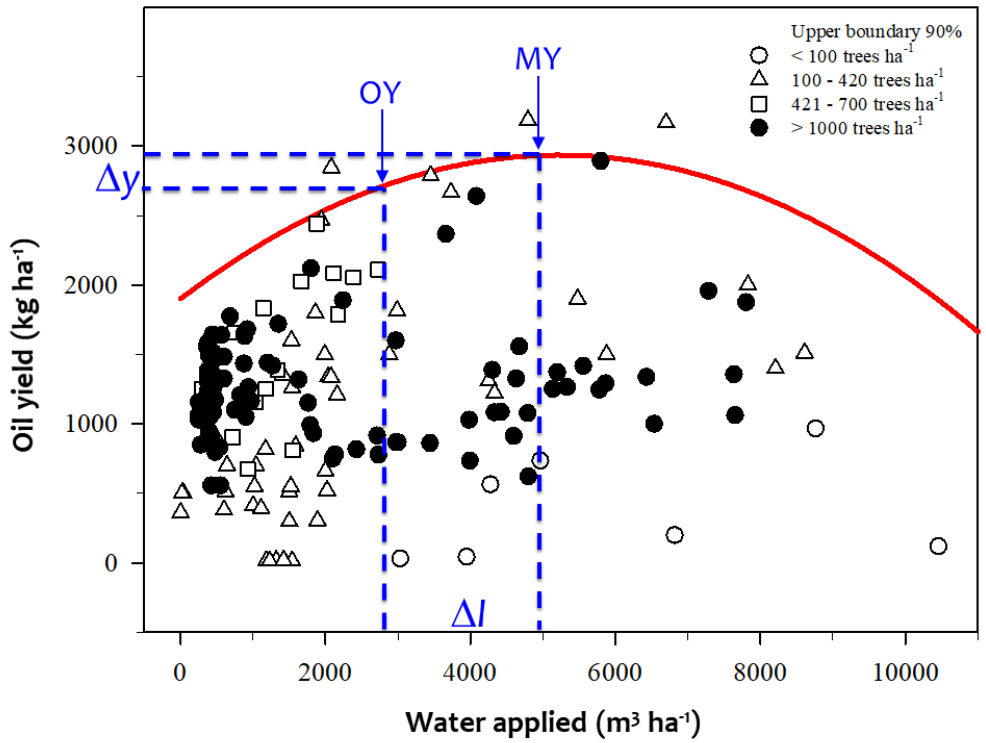
Production target:

- To achieve the most profitable equilibrium between yield and quality
- To control vigor
- Maximum orchard lifespan

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The economic factor

$$WP_c = \frac{\text{yield}}{\text{TWU}} \qquad EWP_c = \frac{\text{Profit}}{\text{TWU}}$$



The optimum option is to irrigate until null marginal benefit:
remaining below the threshold for the cost of applying ΔI being greater than the market value of Δy.

Barker et al. (2003)

Rather than to increase WP_c, our aim should be to increase the economic water productivity, EWP_c

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A Case Study

Agricultural Water Management 187 (2017) 47–56

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Financial assessment of adopting irrigation technology for plant-based regulated deficit irrigation scheduling in super high-density olive orchards

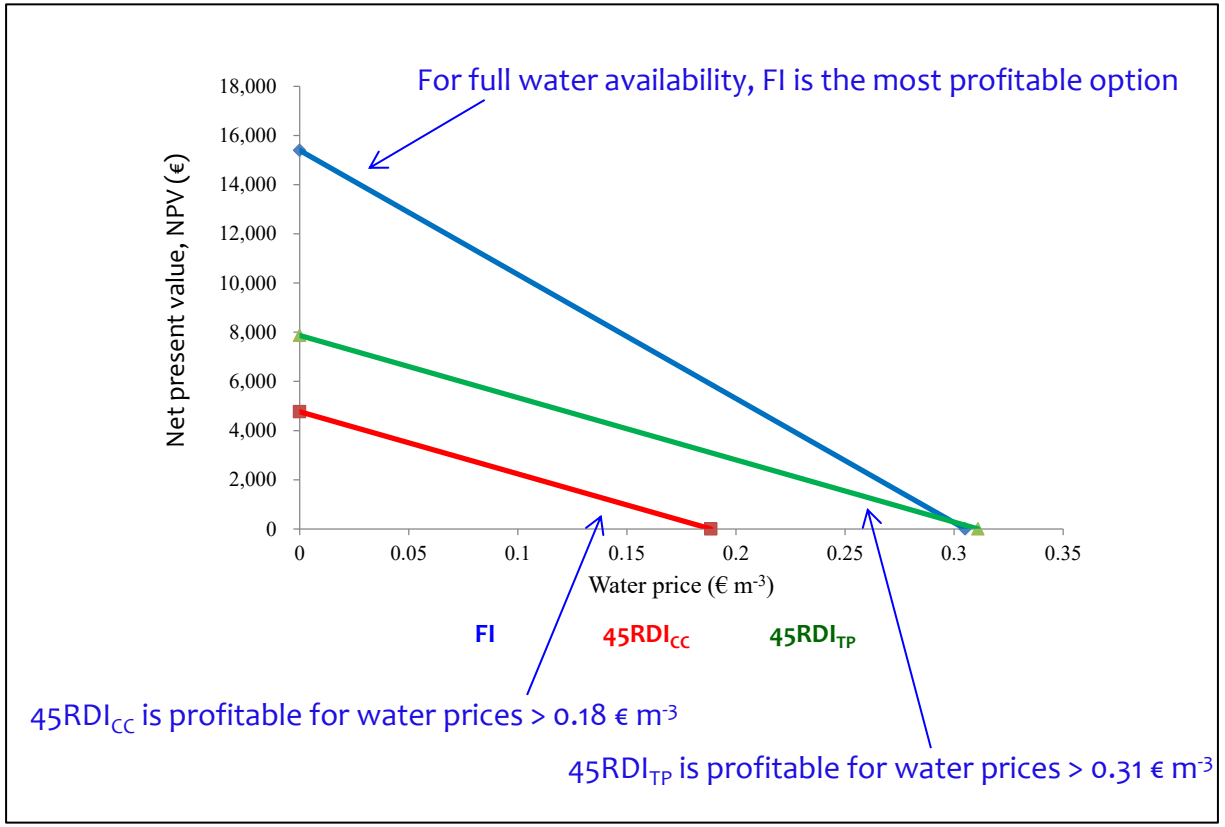
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[b] Irrigation and Crop Ecophysiology Group, Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC), Avenida Reina Mercedes 10, 41012, Seville, Spain
[c] Dept. Economía de la Empresa, Área de Economía, Sociología y Política Agraria, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 48, 30203, Cartagena, Spain

Table 3
Total annual costs for each decision support technology.

	Irrigation Technology		
	TDV	SF	TP
EAC (€ year^{-1} ha^{-1})	531	440	204

TDV: Trunk Diameter Variation; SF: Sap Flow; TP: Leaf Turgor Pressure.



$45RDI_{CC}$ = 45RDI scheduled with the crop coefficient approach

$45RPI_{TP}$ = 45RDI scheduled with turgor pressure (ZIM) probes

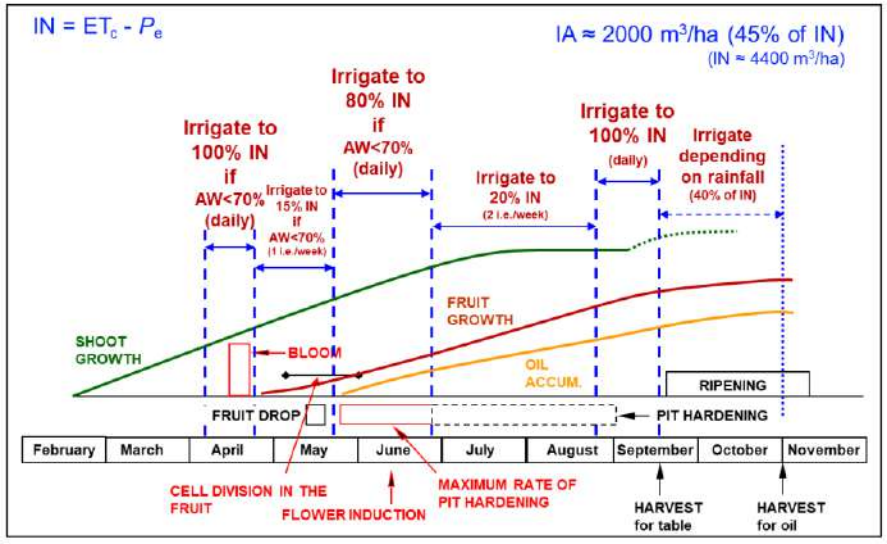
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A Case Study

The Sanabria orchard



1667 'Arbequina' trees ha^{-1}



Agricultural Water Management 237 (2020) 106074

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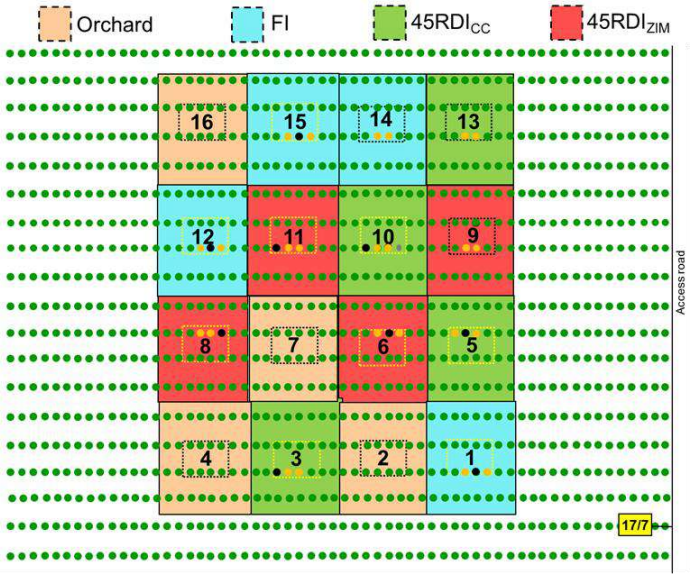
Water use indicators and economic analysis for on-farm irrigation decision: A case study of a super high density olive tree orchard

J.E. Fernández[a,*], F. Alcon[b], A. Diaz-Espejo[a], V. Hernandez-Santana[a], M.V. Cuevas[a]

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[b] Departamento de Economía de la Empresa, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain

Orchard (SDI)	70 % IN
100 % ET_c	100 % IN
60RDI	60 % IN
30RDI	30% IN

2013-1015



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A Case Study

Year	Irrigation amount (mm)		ET_o (mm)	*P* (mm)
	FI	45RDI		
2013	367.6 (85%)*	197.9 (46%)	1464.3	476.4
2014	462.9 (92%)	238.2 (47%)	1437.6	549.4
2015	585.5 (101%)	287.0 (50%)	1581.3	237.6
AVG ± SE	472.0 ± 63.1	241.0 ± 25.7	1494.4 ± 44.1	421.1 ± 94.1

Year	Oil yield (kg ha^{-1})	
	FI	45RDI
2013	1557.1	867.6 (56%)
2014	1875.8	1416.9 (76%)
2015	1957.4	1387.4 (71%)
AVG ± SE	1796.8 ± 122.1	1224.0 ± 178.4 (68%)

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A Case Study

2013-2015 Including CAP payment				
Concept	FI		45RDI	
	Mean	SD	Mean	SD
Raw materials	797.97	115.47 a	620.00	52.50 b
Labour	786.03	7.19 a	717.22	6.56 b
Machinery	763.38	11.65 a	763.38	11.65 a
Other costs	615.68	117.83 a	434.69	96.94 b
Variable costs (€ ha^{-1})	2,963.06	147.61 a	2,535.29	120.24 b
Fixed costs (€ ha^{-1})	680.11	2.28 a	680.11	2.28 a
Opportunity costs (€ ha^{-1})	381.32	2.95 a	372.76	2.40 b
Total costs (€ ha^{-1})	**4024.482**	**149.4404 a**	**3588.16**	**121.70 b**
Total revenues (€ ha^{-1})	5,989.94	1,319.96 a	4,324.59	904.84 b
Gross Margin	3,026.89	1,196.27 a	1,789.29	860.93 b
Net Margin	2,346.78	1,197.13 a	1,109.19	862.81 b
Benefit (€ ha^{-1})	**1,965.46**	**1,194.71 a**	**736.42**	**862.08 b**
$GEWP_I$ (€ m^{-3})	0.65	0.26 a	0.72	0.31 a
$NEWP_I$ (€ m^{-3})	0.50	0.25 a	0.43	0.34 a
EWP_I (€ m^{-3})	**0.42**	**0.25 a**	**0.28**	**0.35 a**

- The benefit was much greater in FI than in 45RDI because the costs were similar, but the oil production was 32 % greater in FI

- There was no difference in EWP_I (?)

Is FI more advisable than 45RDI?

Yes, if enough water available at low price.

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A Case Study

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EWP_I (€ m^{-3})	**0.42**	**0.25 a**	**0.28**	**0.35 a**

- The profitability of SHD olive orchards will be jeopardized without the EU subsidy.

766 € ha^{-1} $year^{-1}$

Villanueva et al. (2015)

- If the cost of the water reservoir is taken into account, the benefits can be negligible.

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A Case Study

2013-2015 Including CAP payment				
Concept	FI		45RDI	
	Mean	SD	Mean	SD
Raw materials	797.97	115.47 a	620.00	52.50 b
Labour	786.03	7.19 a	717.22	6.56 b
Machinery	763.38	11.65 a	763.38	11.65 a
Other costs	615.68	117.83 a	434.69	96.94 b
Variable costs (€ ha^{-1})	2,963.06	147.61 a	2,535.29	120.24 b
Fixed costs (€ ha^{-1})	680.11	2.28 a	680.11	2.28 a
Opportunity costs (€ ha^{-1})	381.32	2.95 a	372.76	2.40 b
Total costs (€ ha^{-1})	**4024.482**	**149.4404 a**	**3588.16**	**121.70 b**
Total revenues (€ ha^{-1})	5,989.94	1,319.96 a	4,324.59	904.84 b
Gross Margin	3,026.89	1,196.27 a	1,789.29	860.93 b
Net Margin	2,346.78	1,197.13 a	1,109.19	862.81 b
Benefit (€ ha^{-1})	**1,965.46**	**1,194.71 a**	**736.42**	**862.08 b**
$GEWP_I$ (€ m^{-3})	0.65	0.26 a	0.72	0.31 a
$NEWP_I$ (€ m^{-3})	0.50	0.25 a	0.43	0.34 a
EWP_I (€ m^{-3})	**0.42**	**0.25 a**	**0.28**	**0.35 a**

- The current tendency is to have less than 1000 trees ha^{-1}

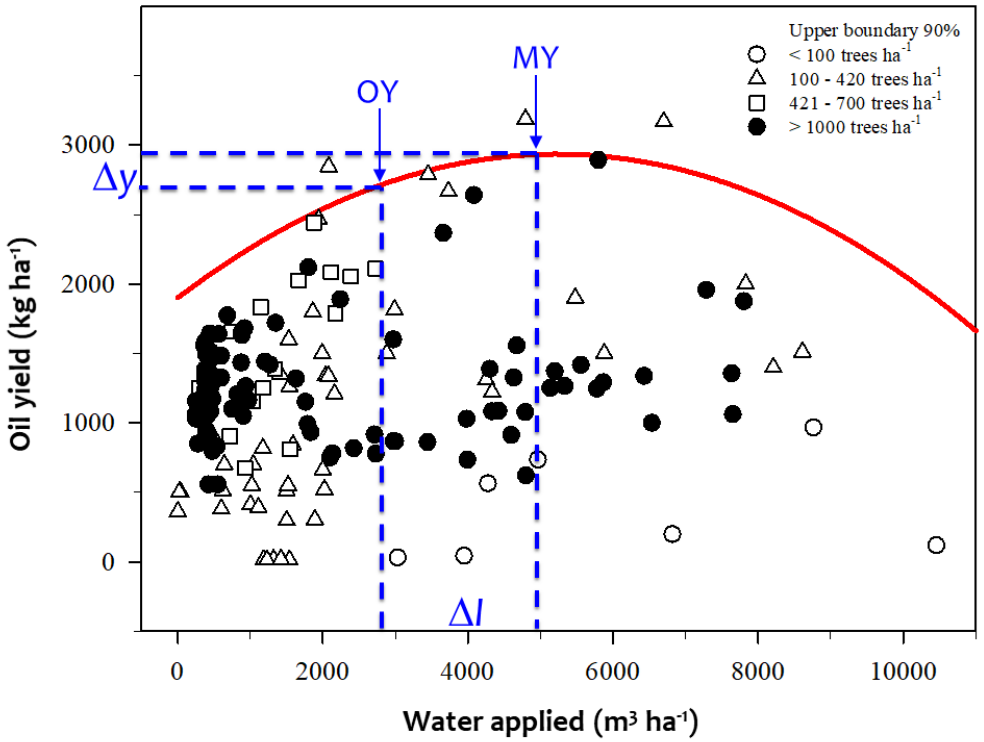
6 m × 1.75 m = 952 trees ha^{-1}

Production costs ≈ 1.0 €/L
instead of 1.3 €/L

Todolivo

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A Case Study



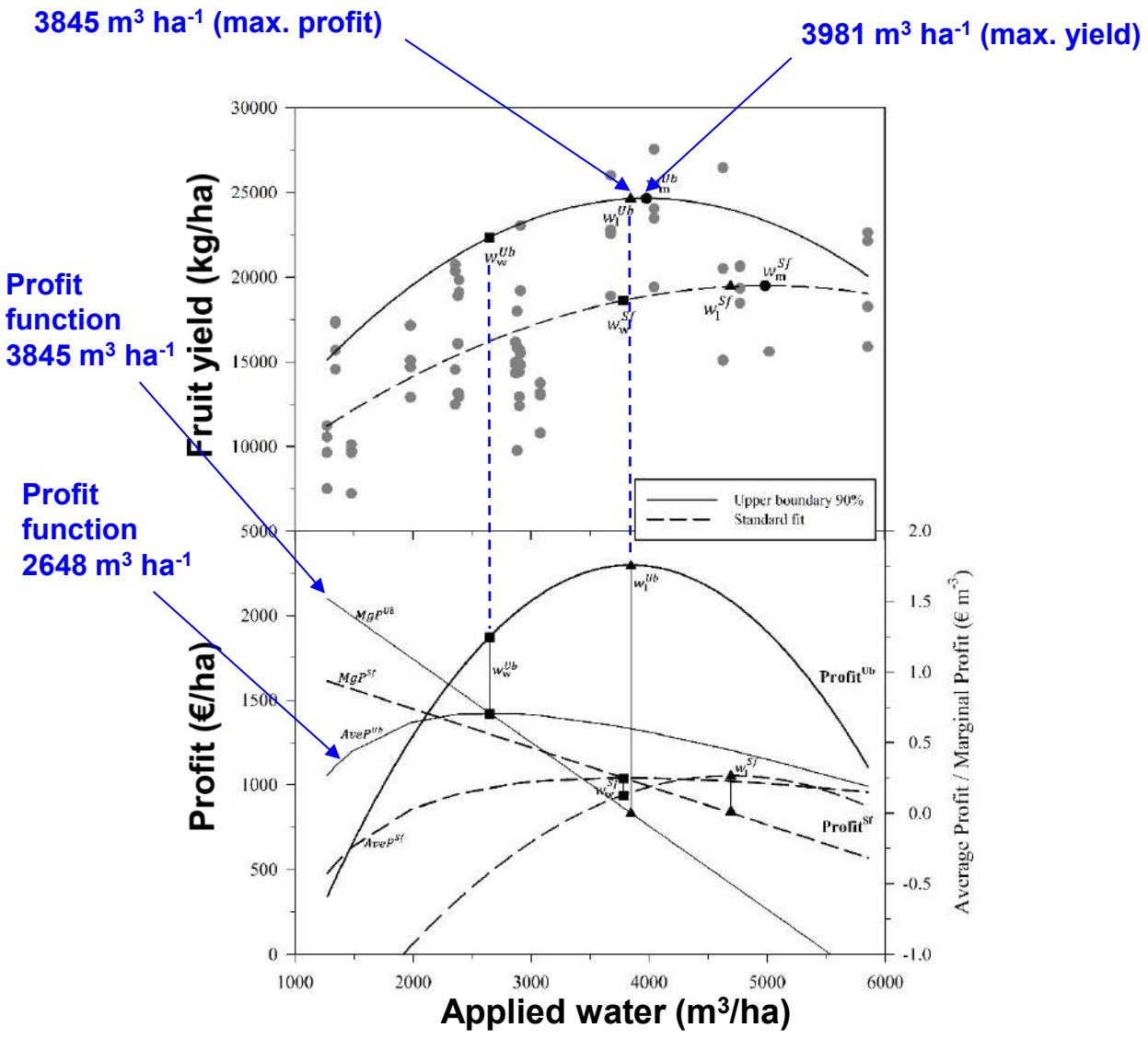
The optimum option is to irrigate until null marginal benefit:
remaining below the threshold for the cost of applying ΔI being greater than the market value of Δy.

Barker et al. (2003)

If they don't pay for quality,
OY is very close to MY.

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The relevance of economic analyses




Agricultural Water Management 237 (2020) 106074

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

ELSEVIER

Water use indicators and economic analysis for on-farm irrigation decision: A case study of a super high density olive tree orchard

J.E. Fernández[a,*], F. Alcon[b], A. Diaz-Espejo[a], V. Hernandez-Santana[a], M.V. Cuevas[a]

[a] Irrigation and Crop Ecophysiology Group, Instituto de Recursos Naturales y Agrobiología de Sevilla, Avenida Reina Mercedes, 10, 41012, Sevilla, Spain
[b] Departamento de Economía de la Empresa, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain

¿What should I do if I have little water?

1. To irrigate a reduced area with 100 % of the irrigation needs?
2. To irrigate a larger area with deficit irrigation?

A 10 ha SHD olive orchard, 1500 m³ ha⁻¹

The best options are to irrigate 3.9 ha with 3845 m³ ha⁻¹, or 5.7 ha with 2648 m³ ha⁻¹

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A Case Study: Conclusions

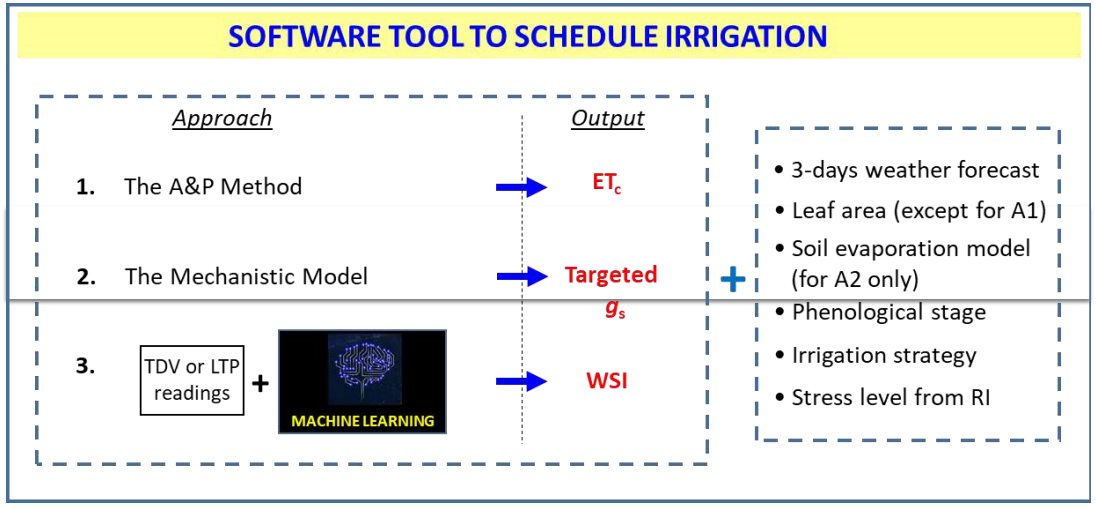
- Information related to WUE and WP is often misleading. This causes controversy on the interpretation of published findings and limits decision making on irrigation management.

- Even if properly chosen and used, indicators related to WP and EWP are helpful but not definitive. They are too simple to explain the complexity of the impact of irrigation on farm profitability.

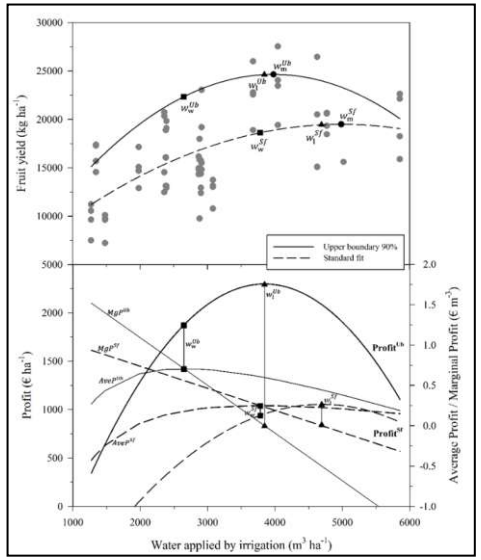
- Decision making for the management of SHD fruit tree orchards must be based on comprehensive and reliable economic analyses.

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Agronomy + economics, to improve irrigation



+



Decision Support System

- The irrigation system
- The irrigation strategy
- The approach to schedule irrigation

https://youtu.be/LgNwd8XI0xE

Enrique Fernández
jefer@irnase.csic.es

Does high-tech irrigation save water?

- High-tech irrigation incresases both WP_c and water savings

At the orchard level? ✓ At the basin level? ✗

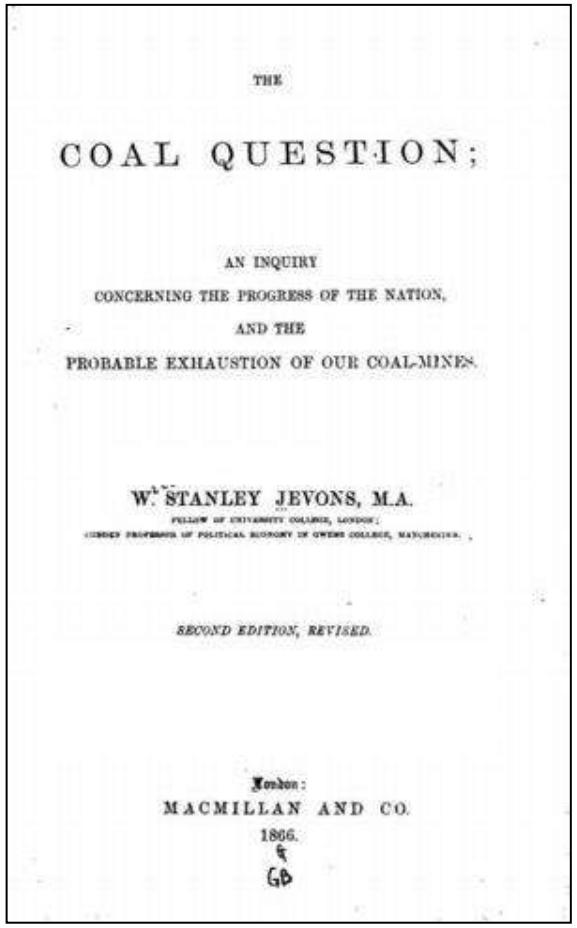
In Andalusia, and in many other areas, the adoption of technically advanced irrigation has led to an increase in the overall water consumption.

The Jevon's paradox



Enrique Fernández
jefer@irnase.csic.es

Does high-tech irrigation save water?



THE

COAL QUESTION;

AN INQUIRY

CONCERNING THE PROGRESS OF THE NATION,

AND THE

PROBABLE EXHAUSTION OF OUR COAL-MINES.

W. STANLEY JEVONS, M.A.

FELLOW OF UNIVERSITY COLLEGE, LONDON;

CORRESPONDING MEMBER OF THE POLITICAL ECONOMY OF OWENS COLLEGE, MANCHESTER.

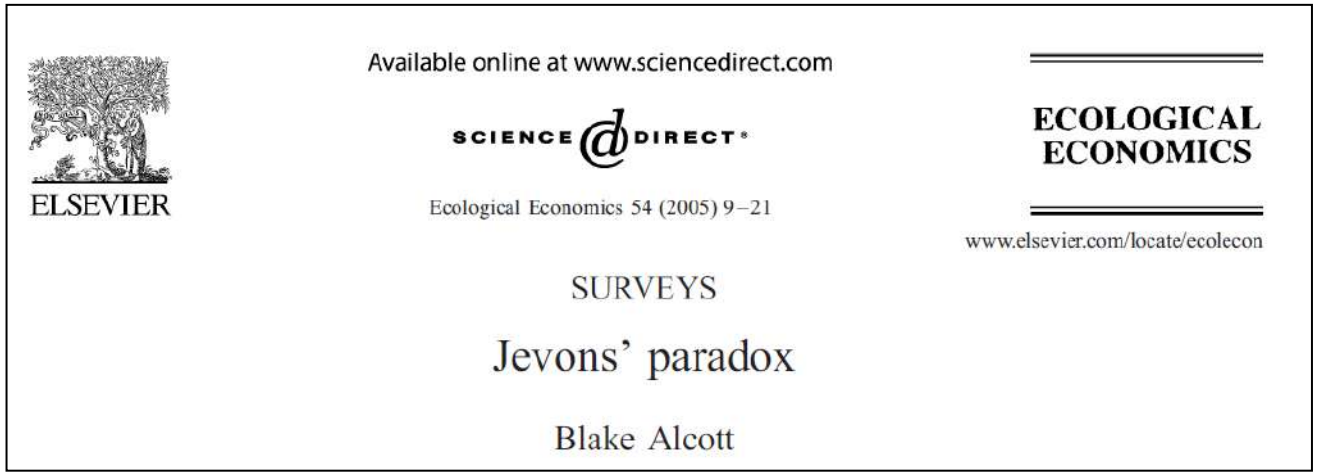
SECOND EDITION, REVISED.

London:

MACMILLAN AND CO.

1866.





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Ecological Economics 54 (2005) 9–21

ELSEVIER

ECOLOGICAL ECONOMICS

www.elsevier.com/locate/ecolecon

SURVEYS

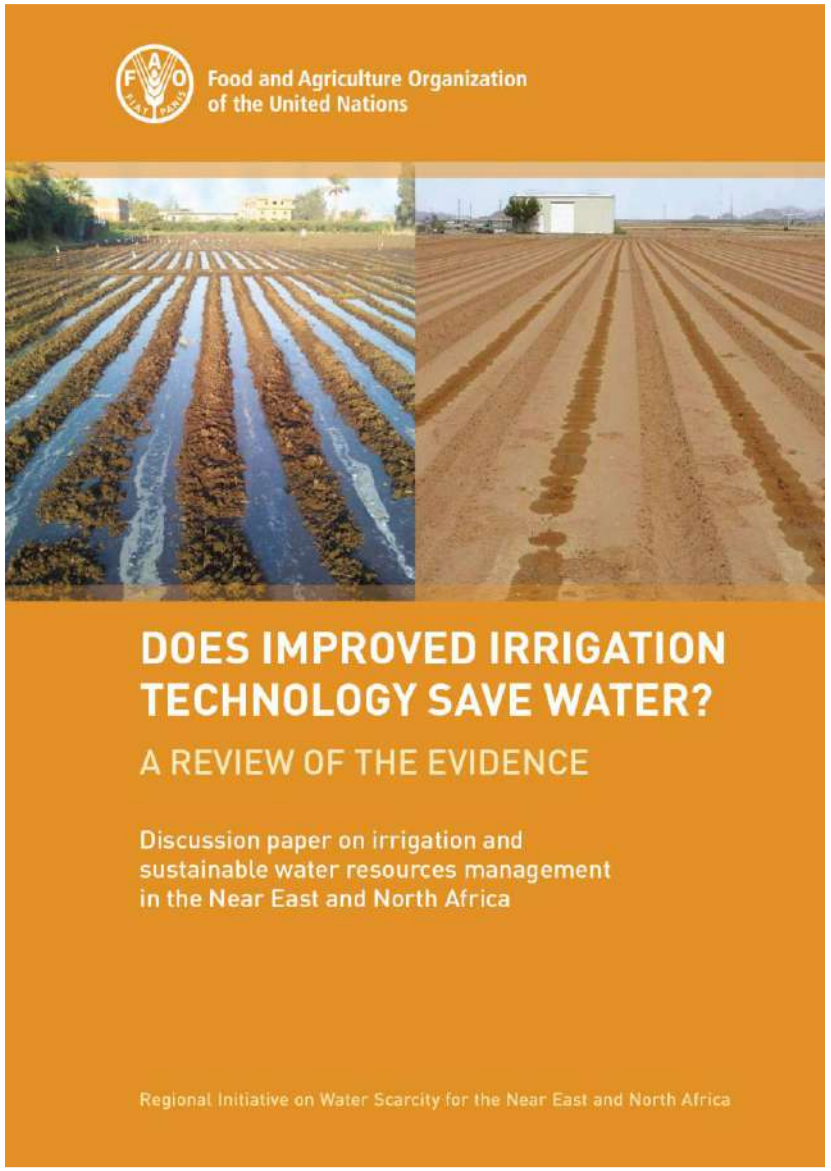
Jevons' paradox

Blake Alcott

The use of coal in engines doing mechanical work increased the overall consumption of coal, iron, and other resources, rather tan "saving" them, as many claimed.

Enrique Fernández
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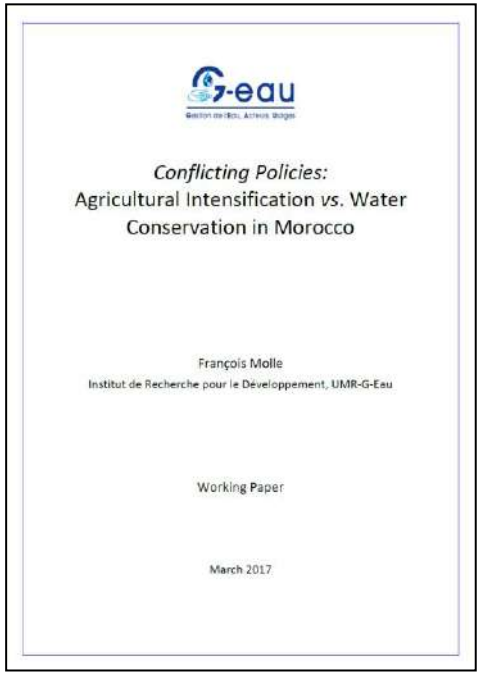
Does high-tech irrigation save water?



It is commonly assumed that the introduction of hi-tech irrigation will save large quantities of water from agriculture that can then be released to other uses.

BUT… *the predictable impact of "more efficient" irrigation is to increase current water consumption, and to increase demand for water – making scarcity both worse and more difficult to manage.*

C. Perry, P. Steduto (2017)



The adoption of high-tech irrigation in an area should be accompanied by rational policies on water consumption.

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Current trends in agricultural studies

1. To increase our knowledge on the crop response to the environment & management

CHAPTER 18

The Olive Tree Under Water Stress: Fitting the Pieces of Response Mechanisms in the Crop Performance Puzzle

Antonio Diaz-Espejo[1], José E. Fernández[1], Jose M. Torres-Ruiz[2], Celia M. Rodriguez-Dominguez[1,3], Alfonso Perez-Martin[1], Virginia Hernandez-Santana[1]

[1]Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC), Seville, Spain; [2]BIOGECO, INRA, University Bordeaux, Pessac, France; [3]University of Tasmania, Hobart, TAS, Australia

Agricultural Water Management 204 (2018) 100–106

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Effect of a regulated deficit irrigation strategy in a hedgerow 'Arbequina' olive orchard on the mesocarp fatty acid composition and desaturase gene expression with respect to olive oil quality

M. Luisa Hernández[a,*], David Velázquez-Palmero[a], M. Dolores Sicardo[a], José E. Fernández[b], Antonio Diaz-Espejo[b], José M. Martínez-Rivas[a]

Enrique Fernández
jefer@irnase.csic.es

Current trends in agricultural studies

2. New varieties obtained with CRISPR and other advanced methods

Review > Int J Mol Sci. 2023 Nov 13;24(22):16241. doi: 10.3390/ijms242216241.

CRISPR Variants for Gene Editing in Plants: Biosafety Risks and Future Directions

Ali Movahedi [1], Soheila Aghaei-Dargiri [2], Hongyan Li [1], Qiang Zhuge [1], Weibo Sun [1]

Affiliations + expand

PMID: 38003431 PMCID: PMC10671001 DOI: 10.3390/ijms242216241

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Current trends in agricultural studies

3. Digitalization



Land Use Policy 108 (2021) 105537

Contents lists available at ScienceDirect

Land Use Policy

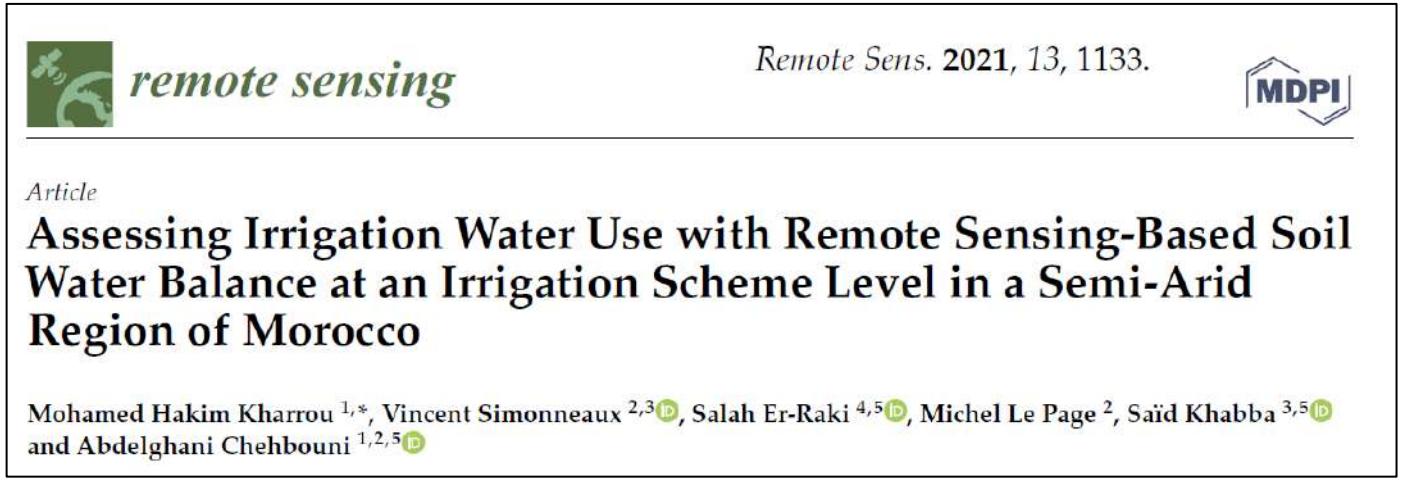
journal homepage: www.elsevier.com/locate/landusepol

Digital transformation of the agrifood system: Quantifying the conditioning factors to inform policy planning in the olive sector

Carlos Parra-López [a,*], Liliana Reina-Usuga [b], Carmen Carmona-Torres [a], Samir Sayadi [a], Laurens Klerkx [c]

Current trends in agricultural studies

4. Remote sensing



remote sensing

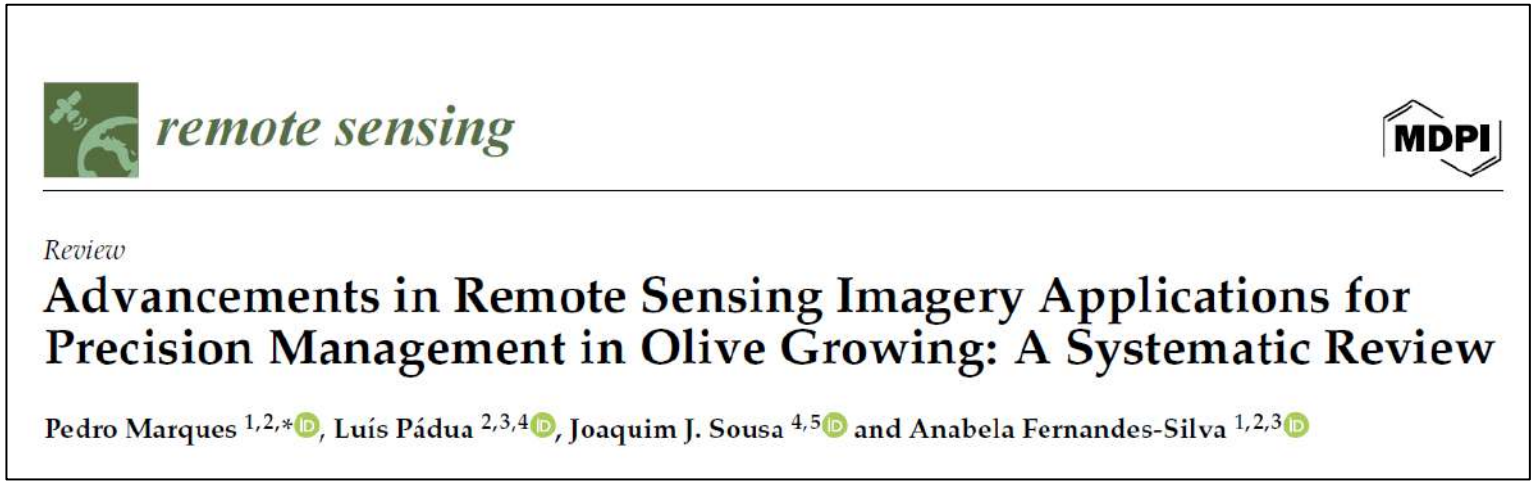
Remote Sens. 2021, 13, 1133.

MDPI

Article

Assessing Irrigation Water Use with Remote Sensing-Based Soil Water Balance at an Irrigation Scheme Level in a Semi-Arid Region of Morocco

Mohamed Hakim Kharrou [1,*], Vincent Simonneaux [2,3], Salah Er-Raki [4,5], Michel Le Page [2], Saïd Khabba [3,5] and Abdelghani Chehbouni [1,2,5]



remote sensing

MDPI

Review

Advancements in Remote Sensing Imagery Applications for Precision Management in Olive Growing: A Systematic Review

Pedro Marques [1,2,*], Luís Pádua [2,3,4], Joaquim J. Sousa [4,5] and Anabela Fernandes-Silva [1,2,3]

Enrique Fernández
jefer@irnase.csic.es

Current trends in agricultural studies

5. Economic & Social impact



Journal of Cleaner Production 355 (2022) 131692

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Assessing the environmental sustainability of Portuguese olive growing practices from a life cycle assessment perspective

Hélia Sales [a,b,*], Filipa Figueiredo [c], Maria Carlota Vaz Patto [b], João Nunes [a]

Current trends in agricultural studies

6. Facing Global Change

remote sensing

Remote Sens. **2022**, *14*, 5430.

MDPI

Review

Twenty Years of Remote Sensing Applications Targeting Landscape Analysis and Environmental Issues in Olive Growing: A Review

Gaetano Messina and Giuseppe Modica *

Agricultural Systems 181 (2020) 102816

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Is new olive farming sustainable? A spatial comparison of productive and environmental performances between traditional and new olive orchards with the model OliveCan

Hanene Mairech[a,b,*], Álvaro López-Bernal[a,c], Marco Moriondo[d], Camilla Dibari[d,e], Luca Regni[b], Primo Proietti[b], Francisco J. Villalobos[a,c], Luca Testi[a]

Enrique Fernández
jefer@irnase.csic.es

Current trends in agricultural studies

7. Behavioural factors affecting the farmers' intention to adopt new irrigation technologies

Smart Agricultural Technology 7 (2024) 100401

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology



Check for updates

Drivers and barriers to the adoption of precision irrigation technologies in olive and cotton farming—Lessons from Messenia and Thessaly regions in Greece

Konstantina Kakkavou *, Marilena Gemtou, Spyros Fountas

Department of Natural Resources Development and Agricultural Engineering, Agricultural University of Athens, Iera Odos 75, 11855 Athens, Greece



The Ecophyisiology and Crop Irrigation (ECOVER) group

Institute for Natural Resources and Agrobiology (IRNAS)
Spanish National Research Council (CSIC)

Enrique Fernández
jefer@irnase.csic.es

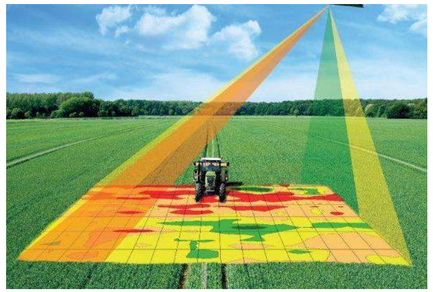


Remote sensing and its application in agriculture, Use of plant sensors in precision agriculture, Application of plant physiology in precision agriculture

Antonio Díaz Espejo

Farmers need new tools

Modernization of agriculture and the use of digital tools have induced the emergence of new concepts:



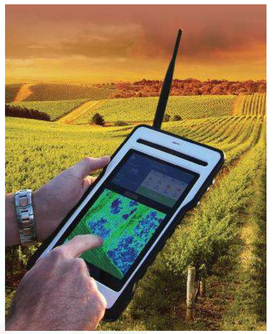
Precision agriculture

Heterogeneity and optimization

Smart agriculture



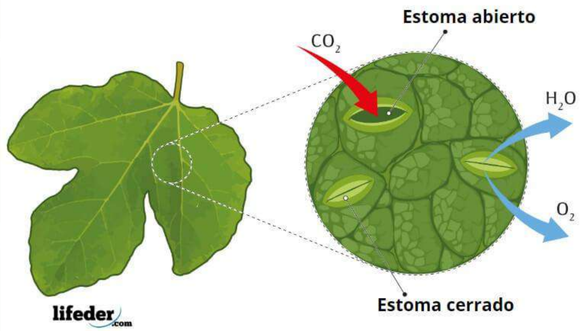
Access to data and their application





Digital agriculture

To generate data with added value



Weak implementation

Why digital agriculture is not widely implemented by farmers?



1 • The average age of farmers.

2 • High cost perception by farmer, companies do not transfer in a convincing way the cost effectiveness of the use of these technologies.



3 • Lack of economical analysis in parallel to scientific studies.



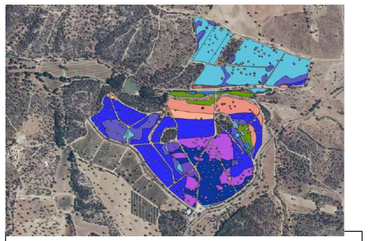
4 • A major issue is that the robustness of the product is not completed yet.



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Toward a precision agriculture

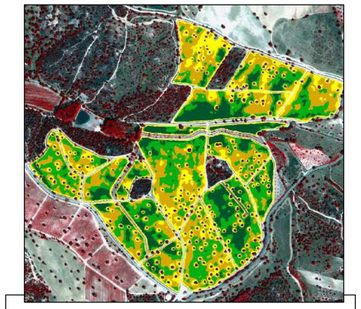


ZONIFICATION
GIS

verde
smart co.

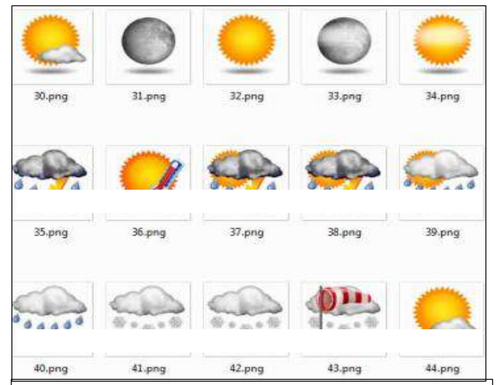


Stations with sensors:
soil, plant, meteo



Remote sensing

Decission Support System (DSS)



Micro weather forecast



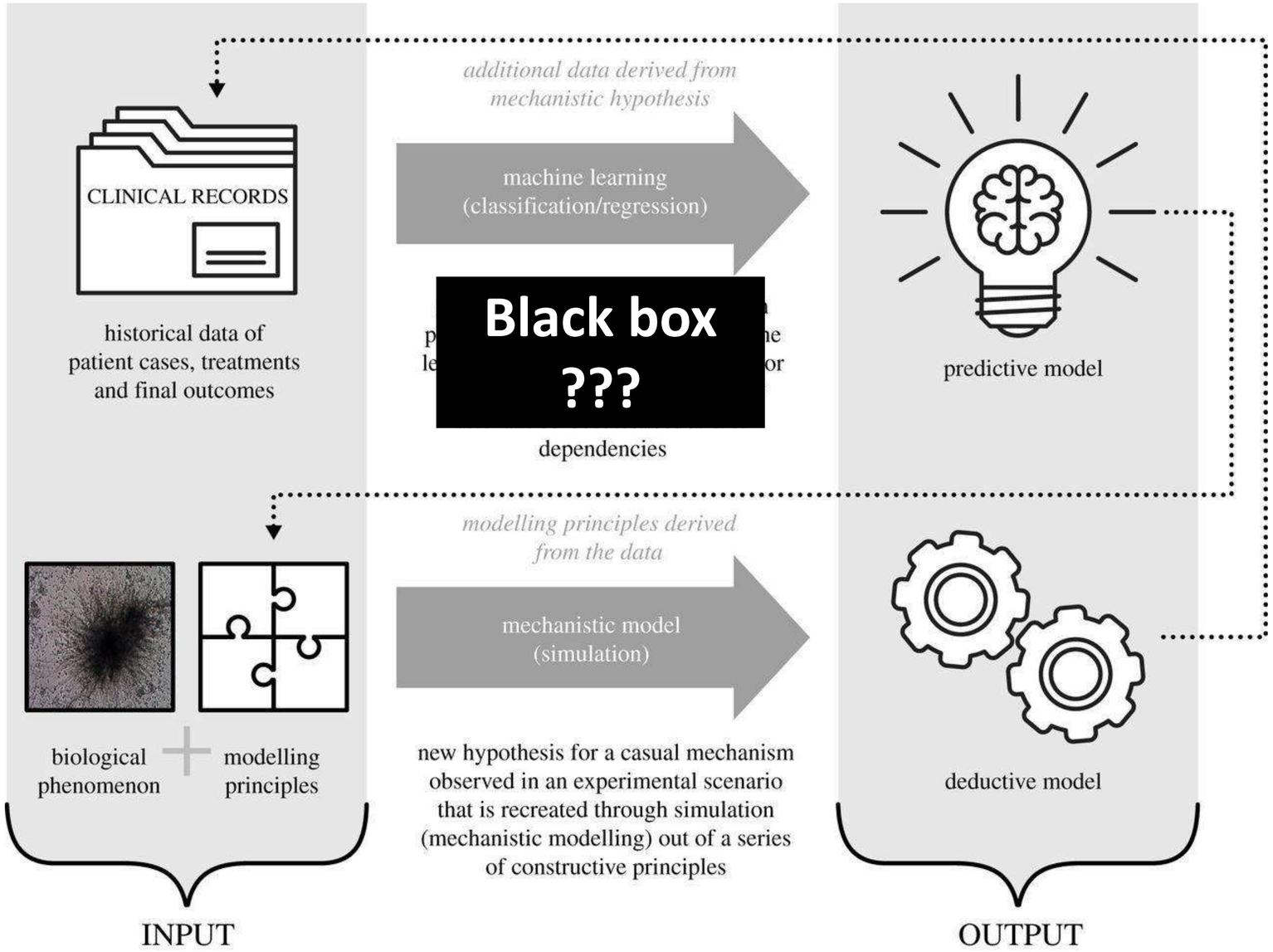
Field data survey

To solve the problems of farmers:
To increase benefits & to save inputs (Water, energy, fertilisers, plant protection products)

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Predictive *vs* deductive models



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Artificial Intelligence works, but …

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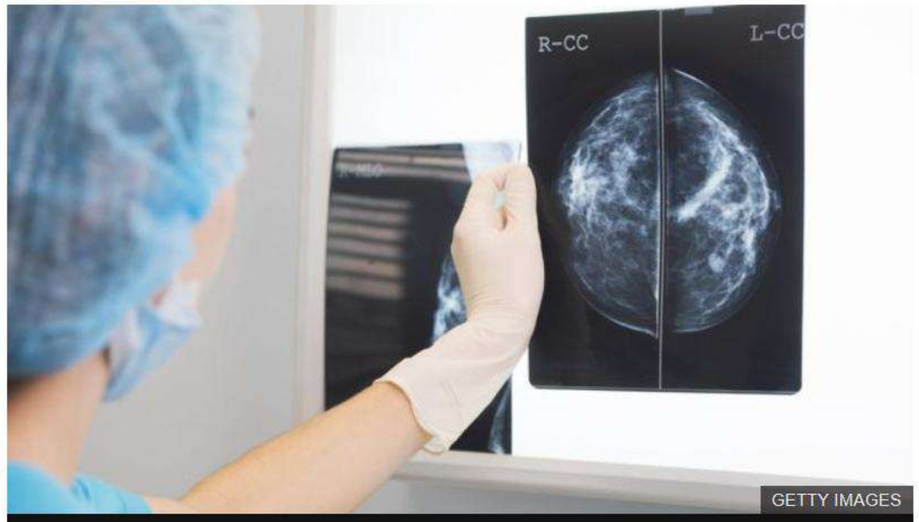
Health

AI 'outperforms' doctors diagnosing breast cancer



Fergus Walsh
Medical correspondent
@BBCFergusWalsh

2 January 2020 Share



AI was as accurate as two doctors working together

Artificial intelligence is more accurate than doctors in diagnosing breast cancer from mammograms, a study in the journal Nature suggests.

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AI can predict if you'll die soon – but we've no idea how it works

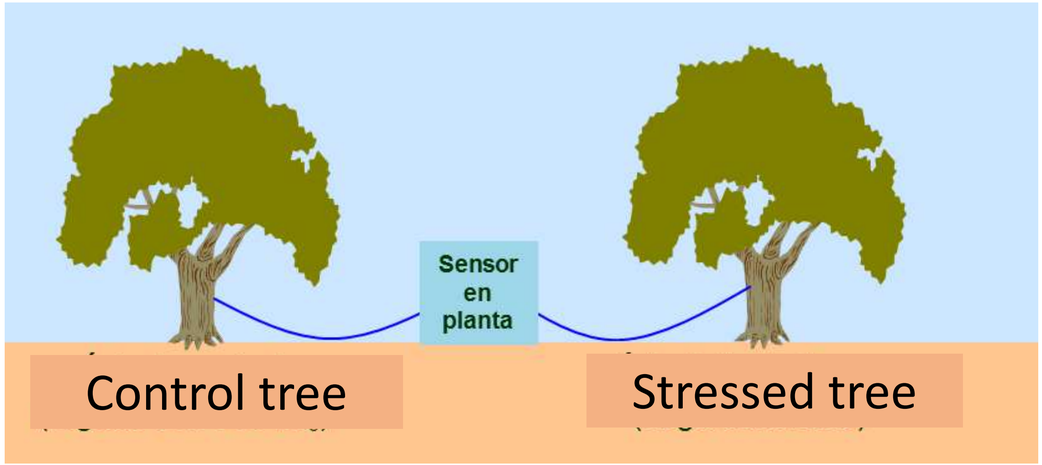
TECHNOLOGY 11 November 2019

By Donna Lu



BURGER/PHANIE/SCIENCE PHOTO LIBRARY

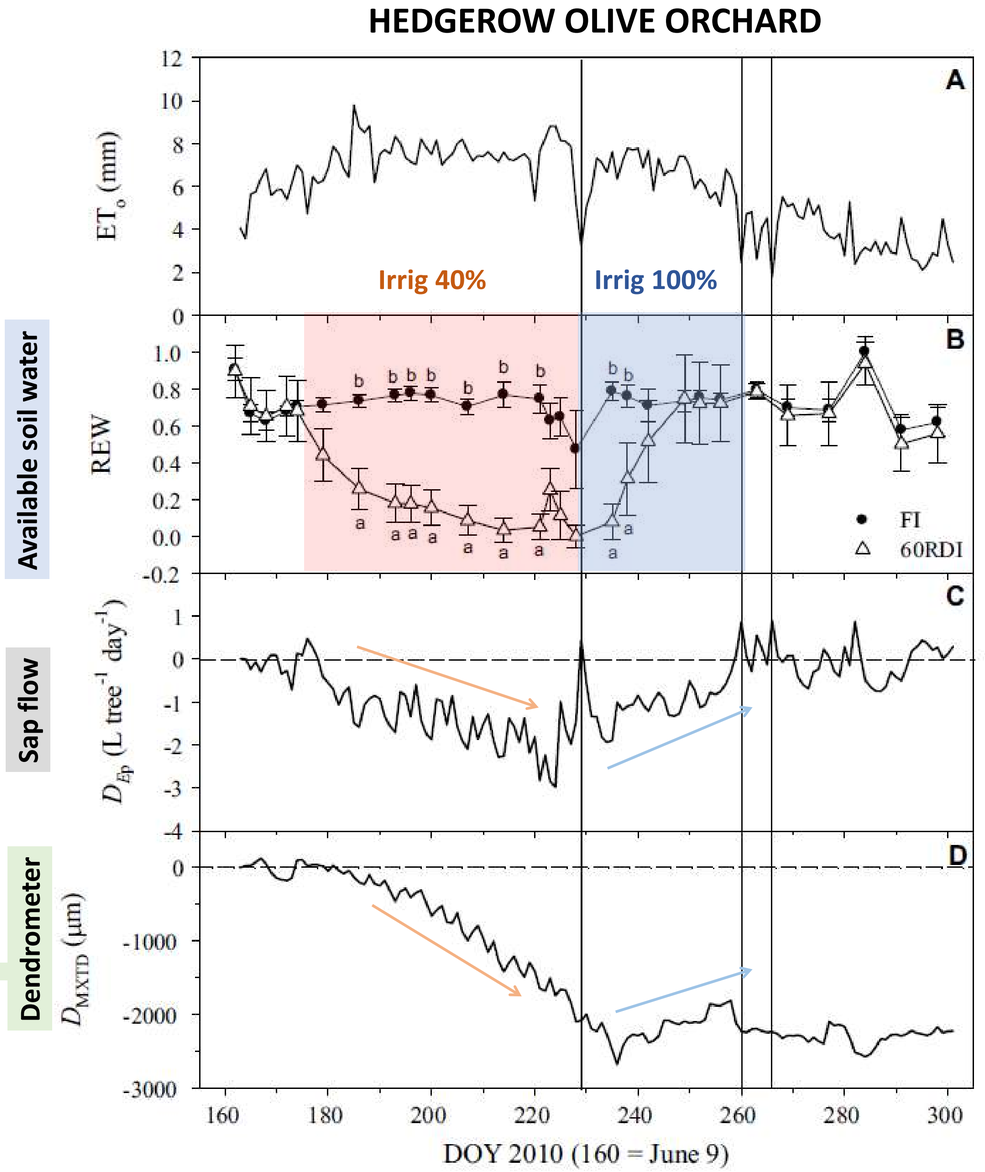
An approach based on plant-based sensors



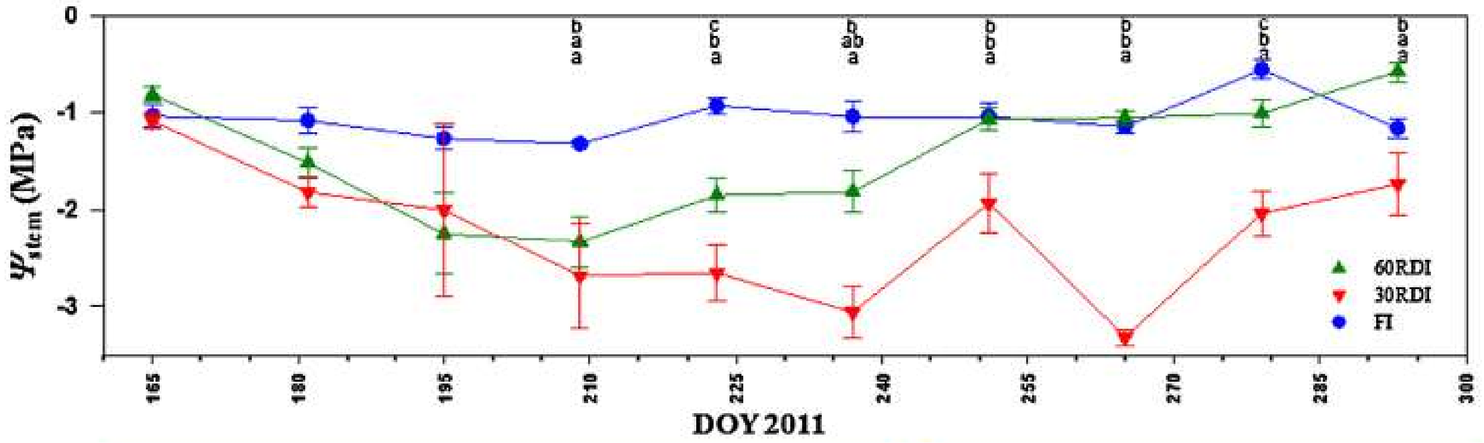
$$\text{Signal Intensity} = \frac{\text{Stressed tree}}{\text{Control tree}}$$

Signal Intensity = Stressed tree – Control tree

SI ↓ = needs irrigation

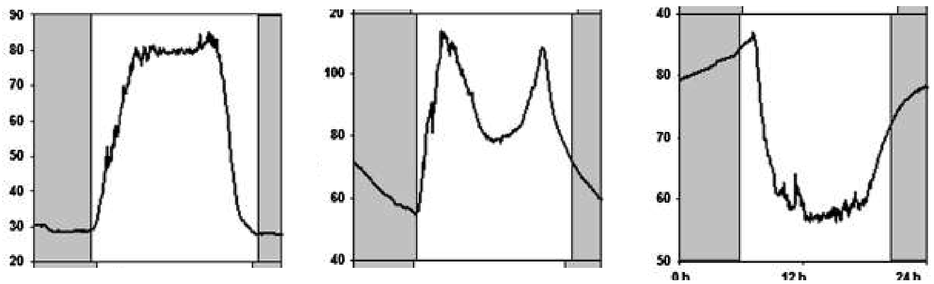


Ψ_{stem}, a classical water stress indicator



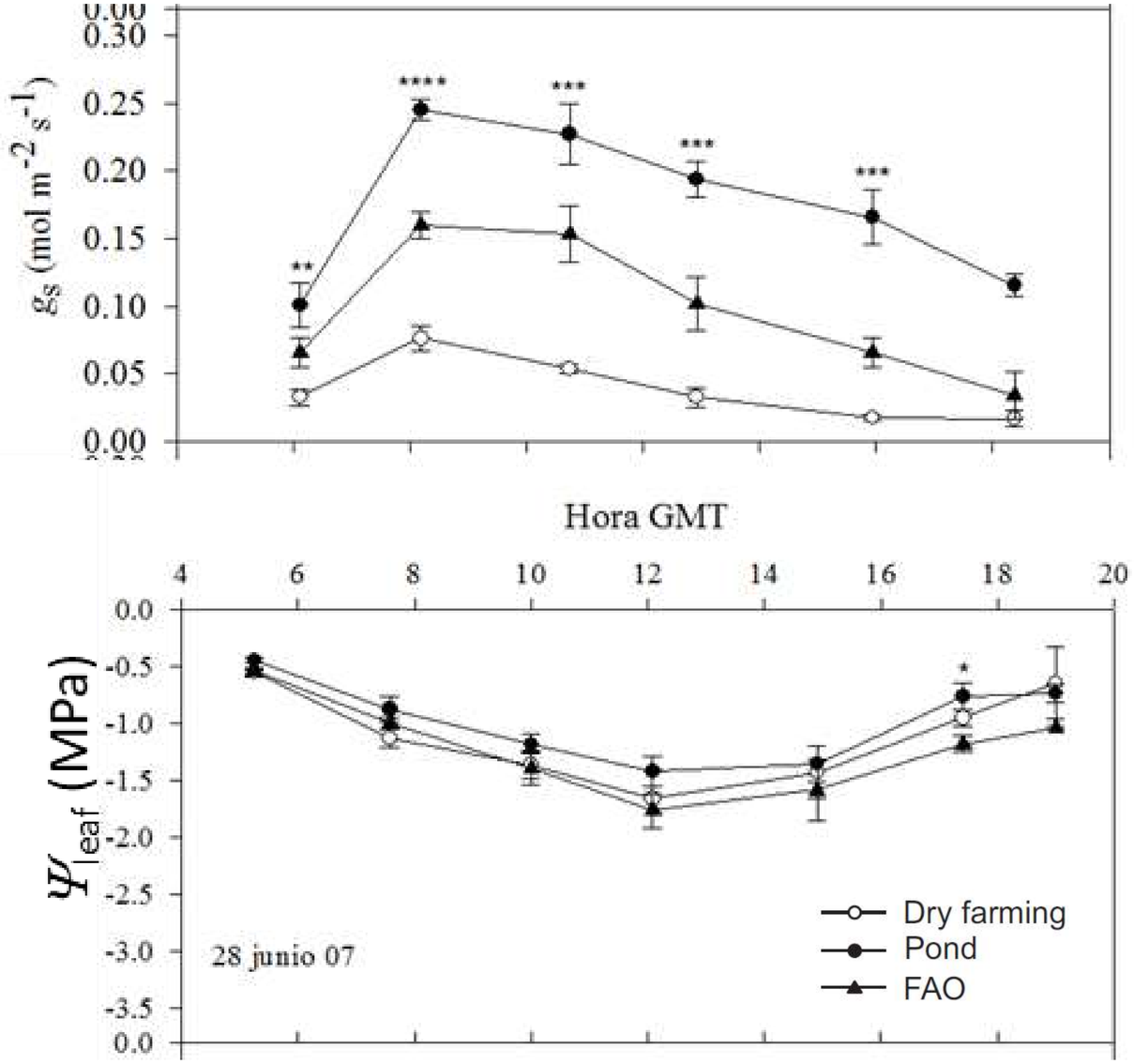
Turgor sensor a plant-based water stress indicator

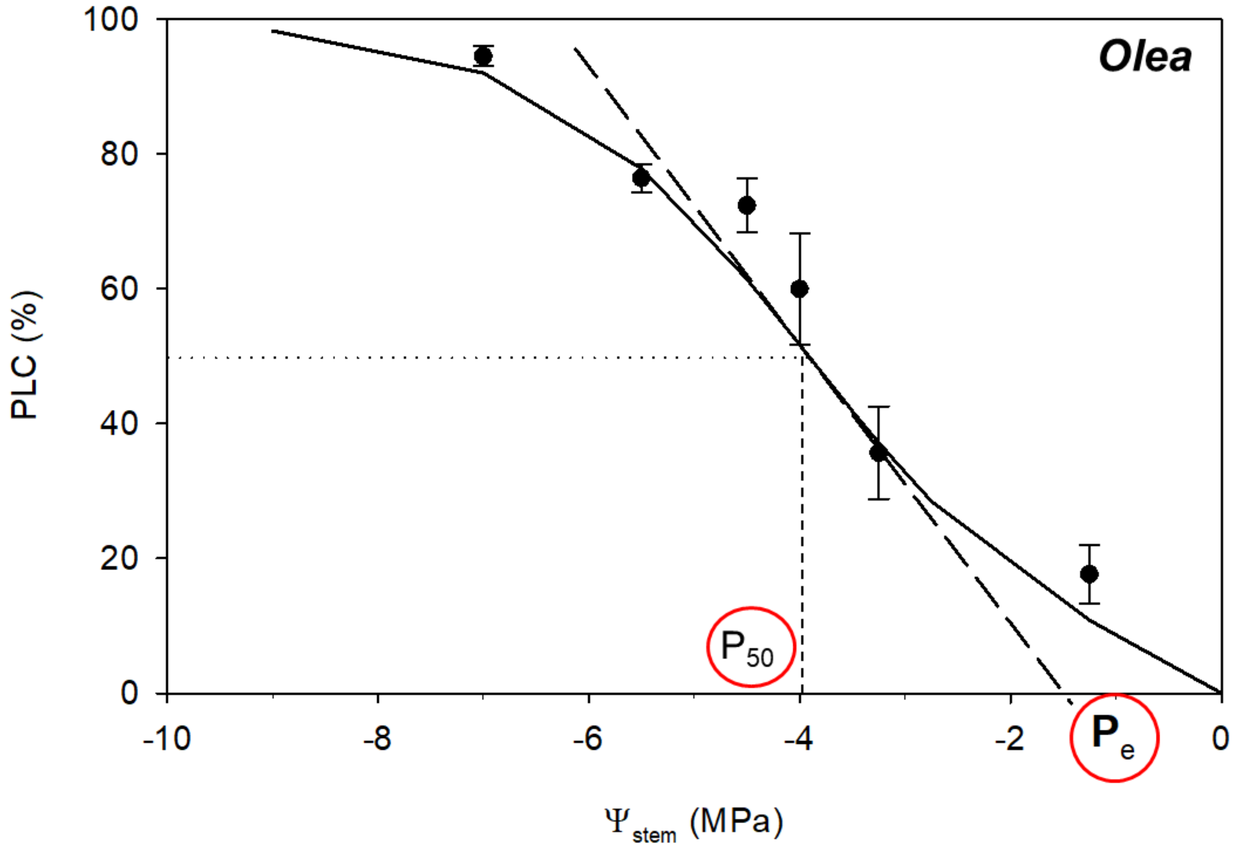




Fernandez et al. (2011)

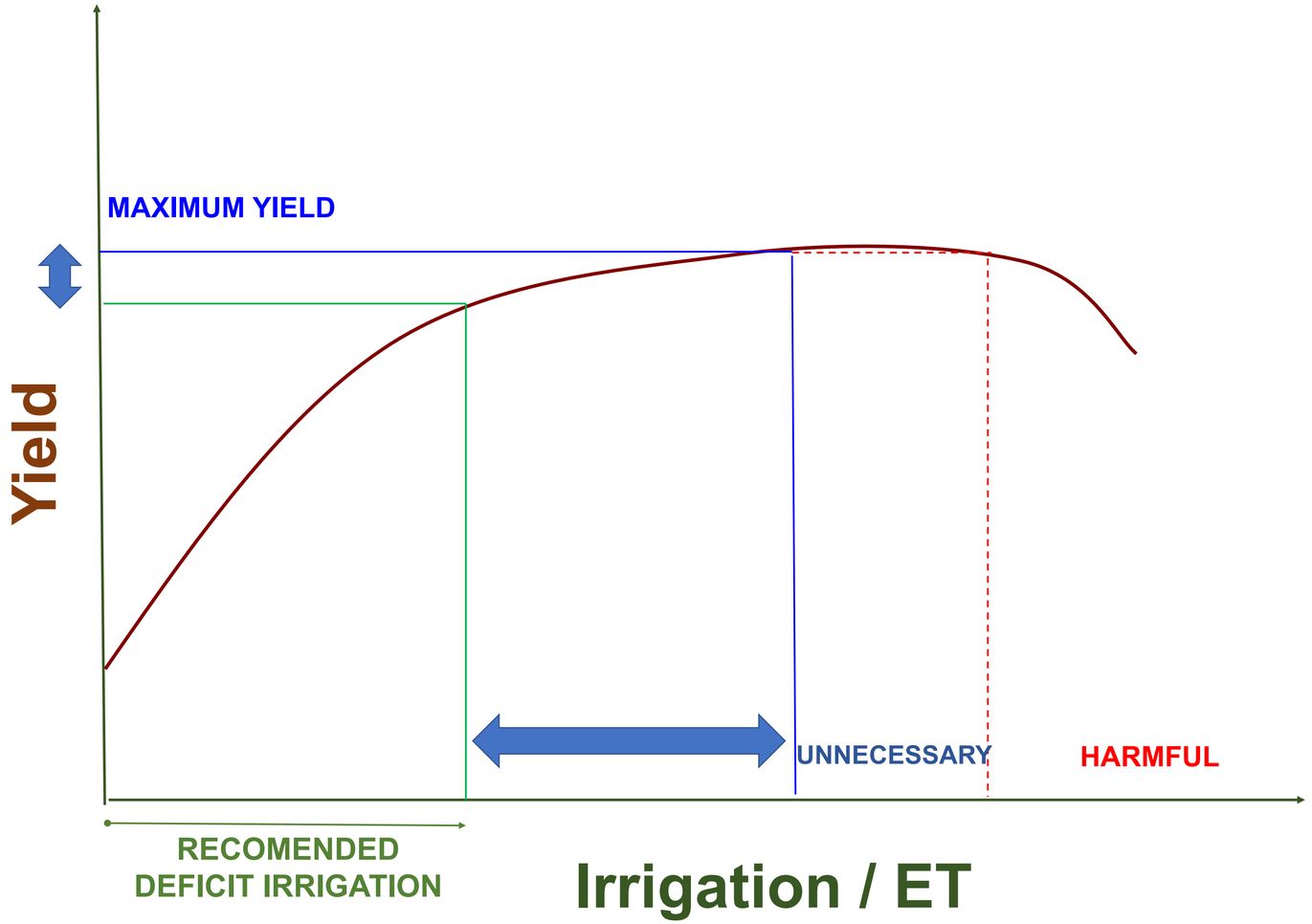
Control of the risk of embolism





How can we decide and apply efectively a deficit irrigation?

Can we do this rationally with the current methodology?



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How are we estimating plant water needs currently?

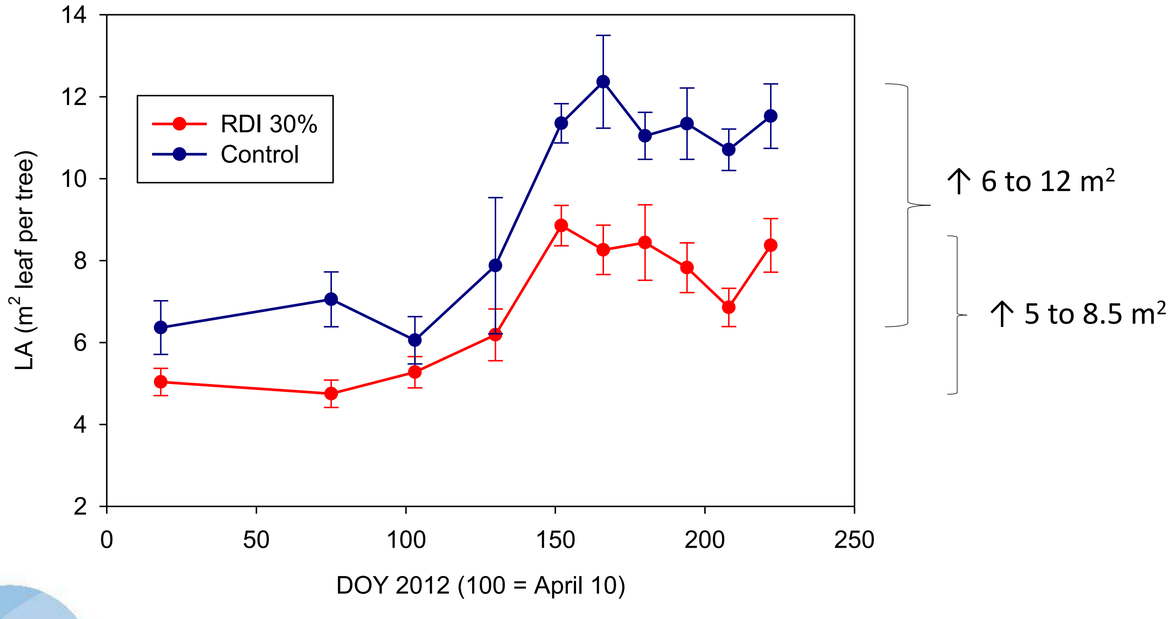
The crop coefficient method (Allen et al., 1998) is the "benchmark"

ET_C= crop evapotranspiration
K_r= reduction coeficcient (plant cover)
K_c= crop coefficient
ET_o= potential evapotranspiration

$$ET_c = K_r K_c ET_o$$

- Irrigation scheduling based on former week meteo conditions
- ET_o often based on reference met stations which are not under reference conditions (grass surface, etc.)

It depends much on the leaf area evolution along the season



It depends on the phenological stage and the physiological response

	K_c	K_r	$K_c K_r$	ET_o* (mm/mes)	ET_c (mm/mes)	ET_c (mm/año)	ET_c (L/arb/día)
Ene	1.16	0.7	0.81	28.73	23.27	605	26.27
Feb	1.06	0.7	0.74	42.05	31.11		38.89
Mar	0.88	0.7	0.62	76.46	47.10		53.18
Abr	0.84	0.7	0.59	98.31	57.81		67.44
May	0.76	0.7	0.53	134.48	71.54		80.77
Jun	0.70	0.7	0.49	153.83	75.38		87.94
Jul	0.63	0.7	0.44	176.56	77.86	357	87.91
Ago	0.63	0.7	0.44	164.48	72.54		81.90
Sep	0.72	0.7	0.50	118.28	59.62		69.55
Oct	0.77	0.7	0.54	72.18	38.91		43.93
Nov	1.07	0.7	0.75	39.03	29.27		34.15
Dic	1.14	0.7	0.80	26.14	20.91		23.61

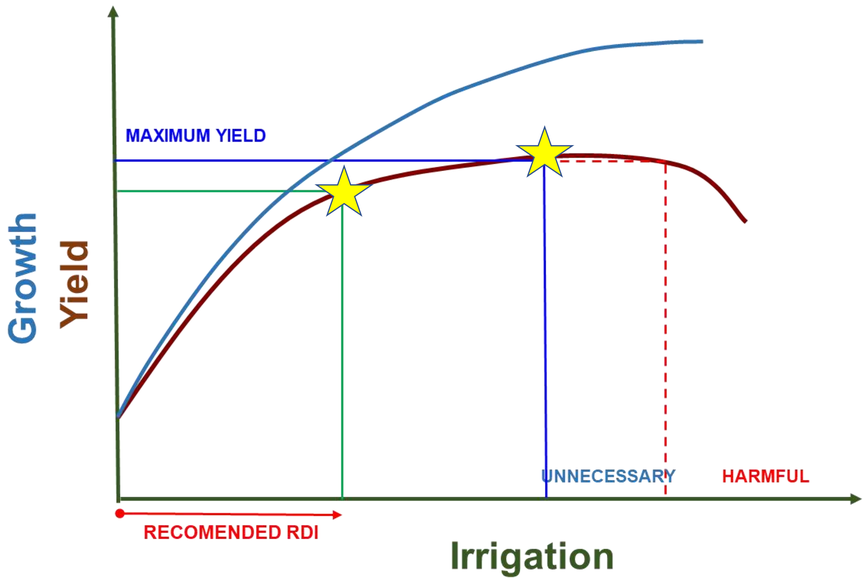
Does the K_c method fulfil our requirements for a precision agriculture?

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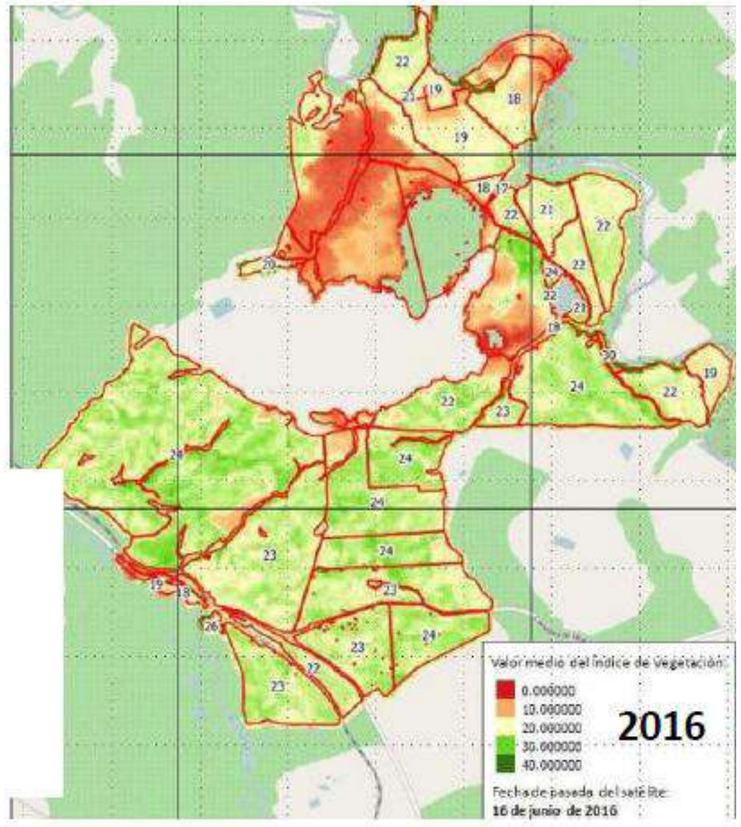
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Questions to be addressed:

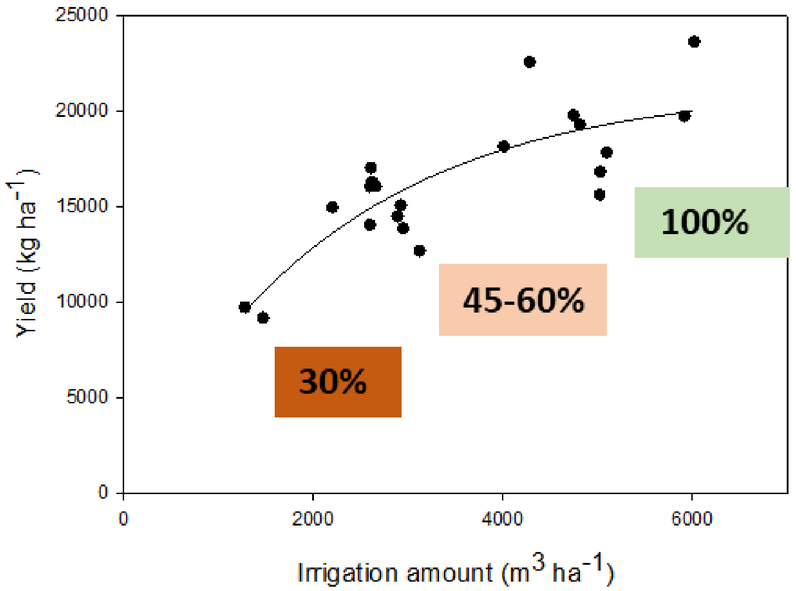
Estimation of both full and deficit water requirements



The issue of heterogeneity

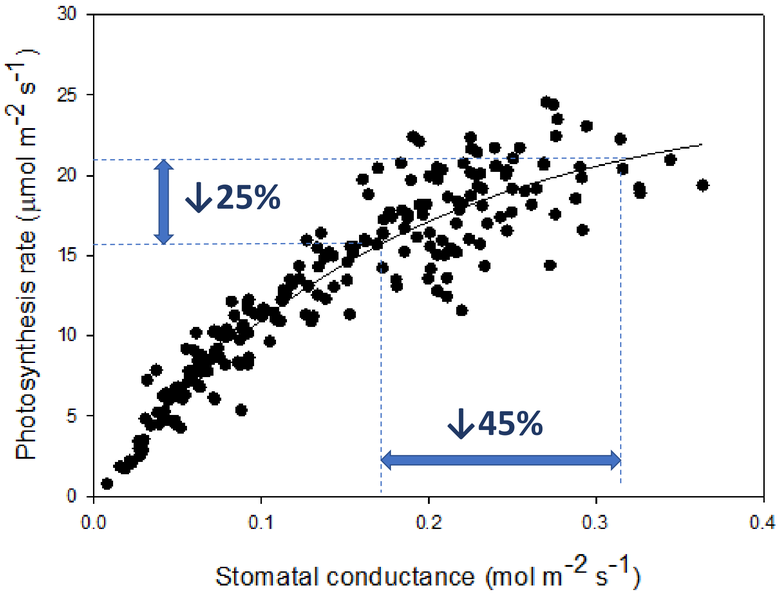


A new approach: the gs-based method



Conceptual basis

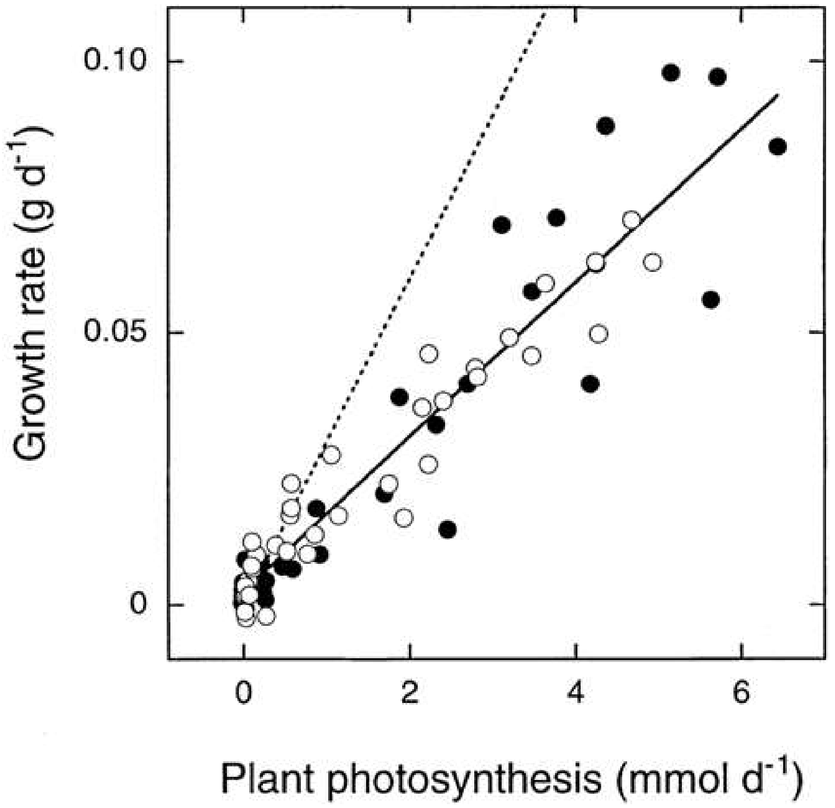
Analogous



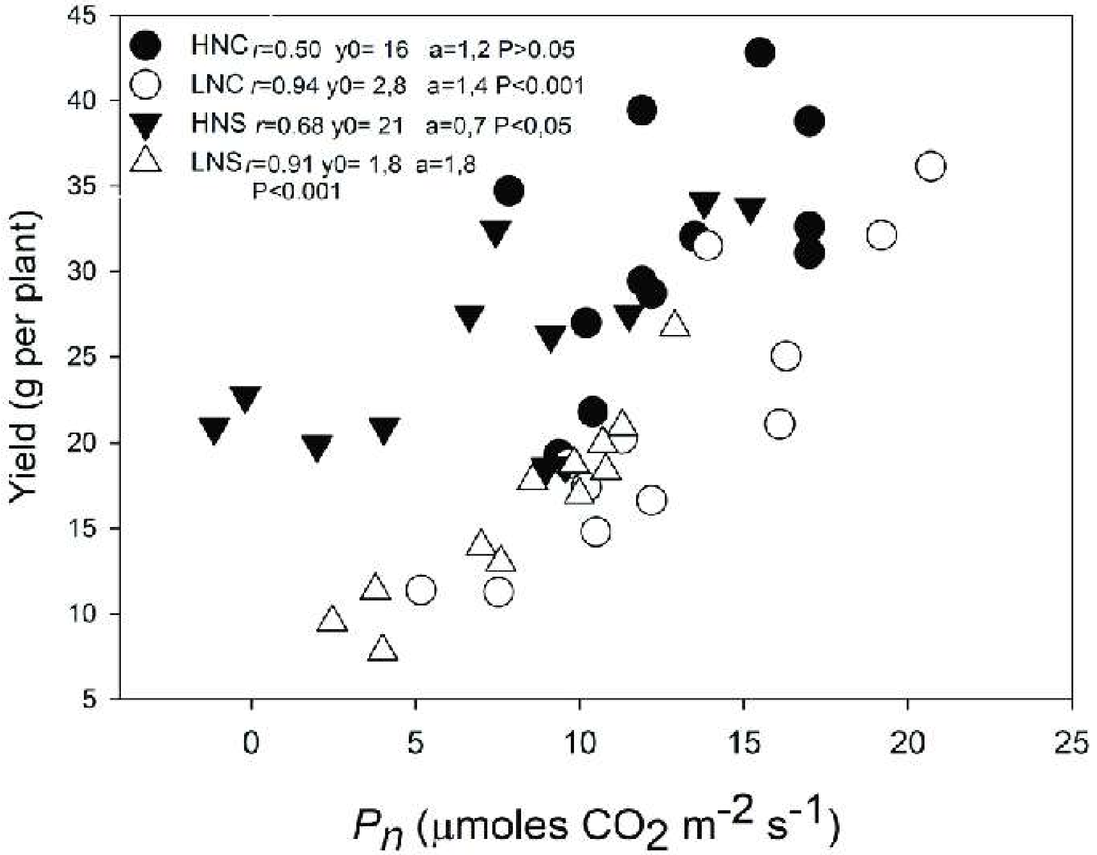
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Photosynthesis and growth

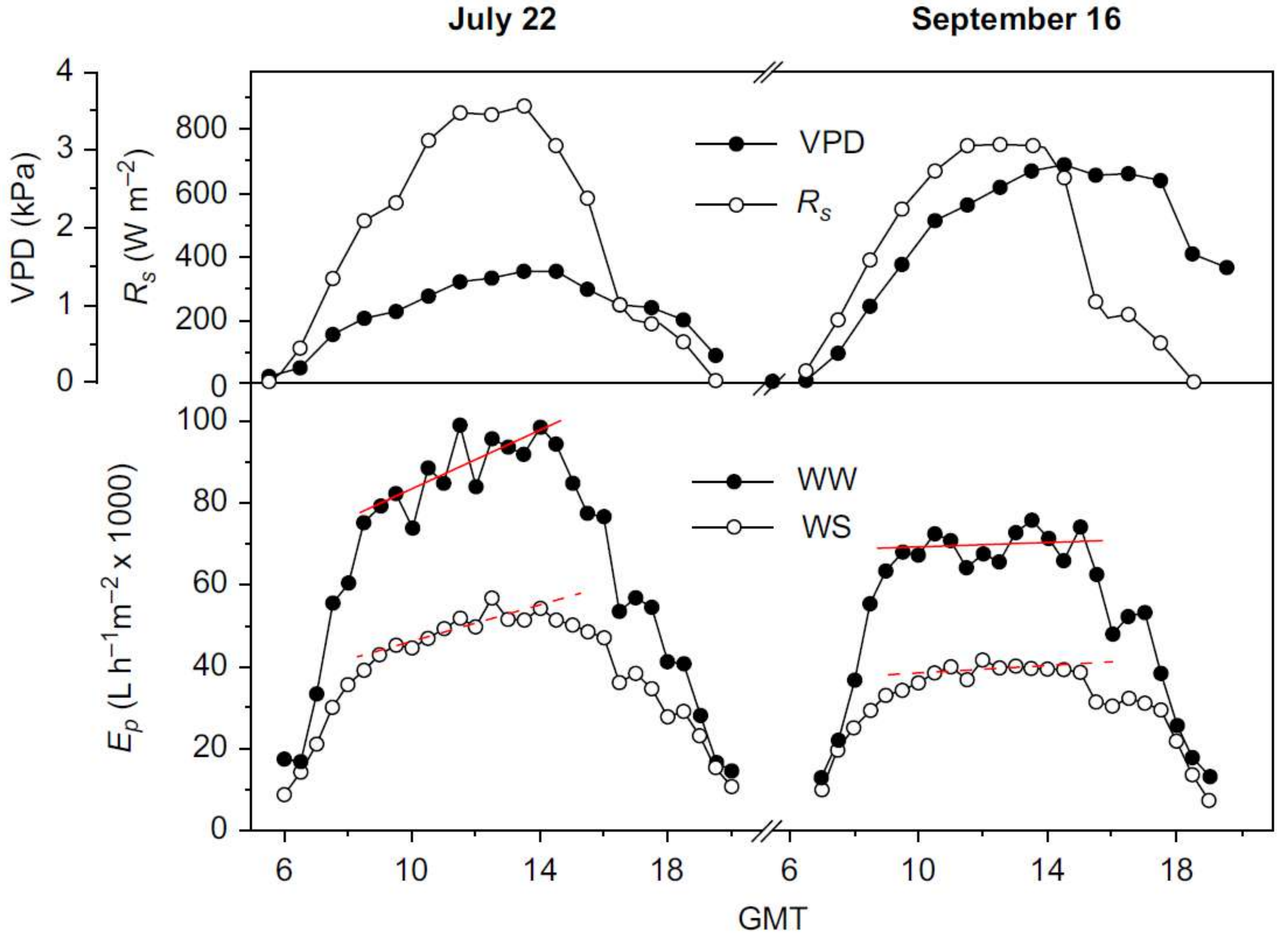


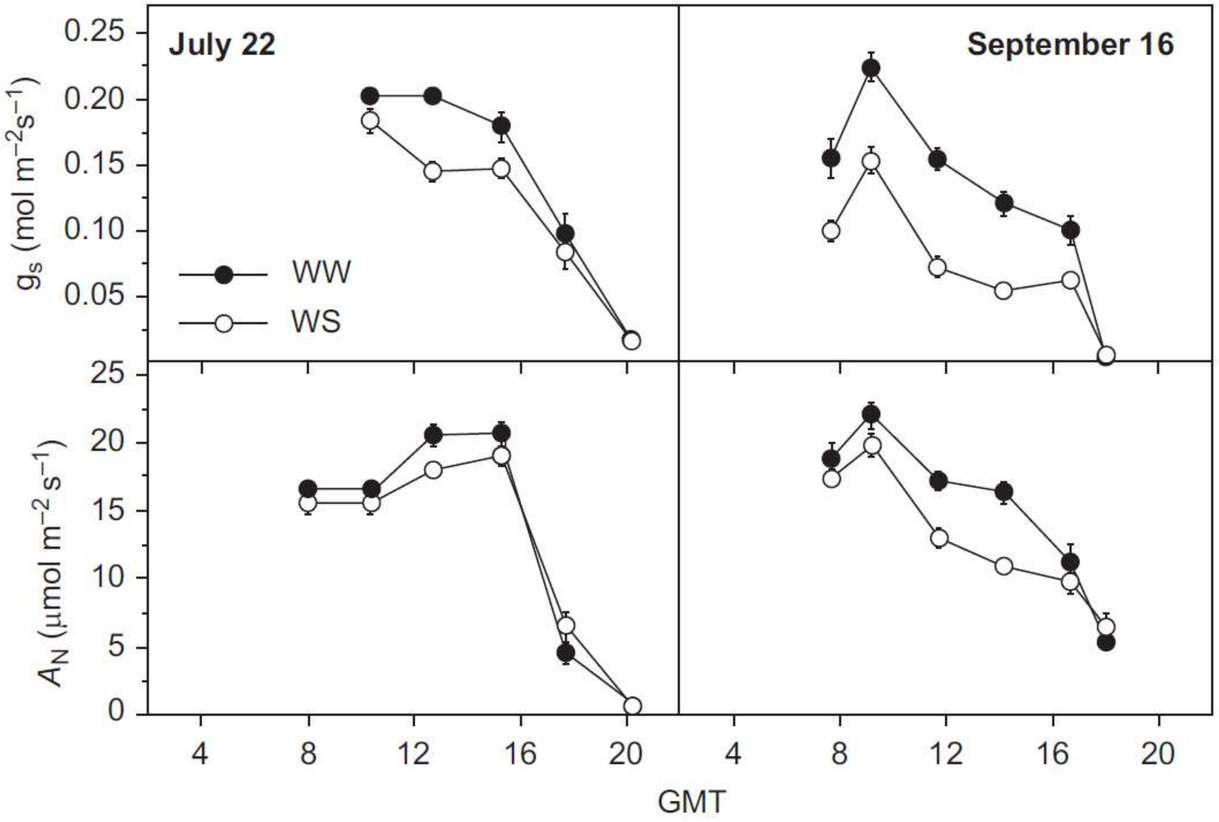
Hikosaka et al., 1999



Bascuñan-Godoy et al., 2018

Real measured use of water by trees





Conceptual scheme

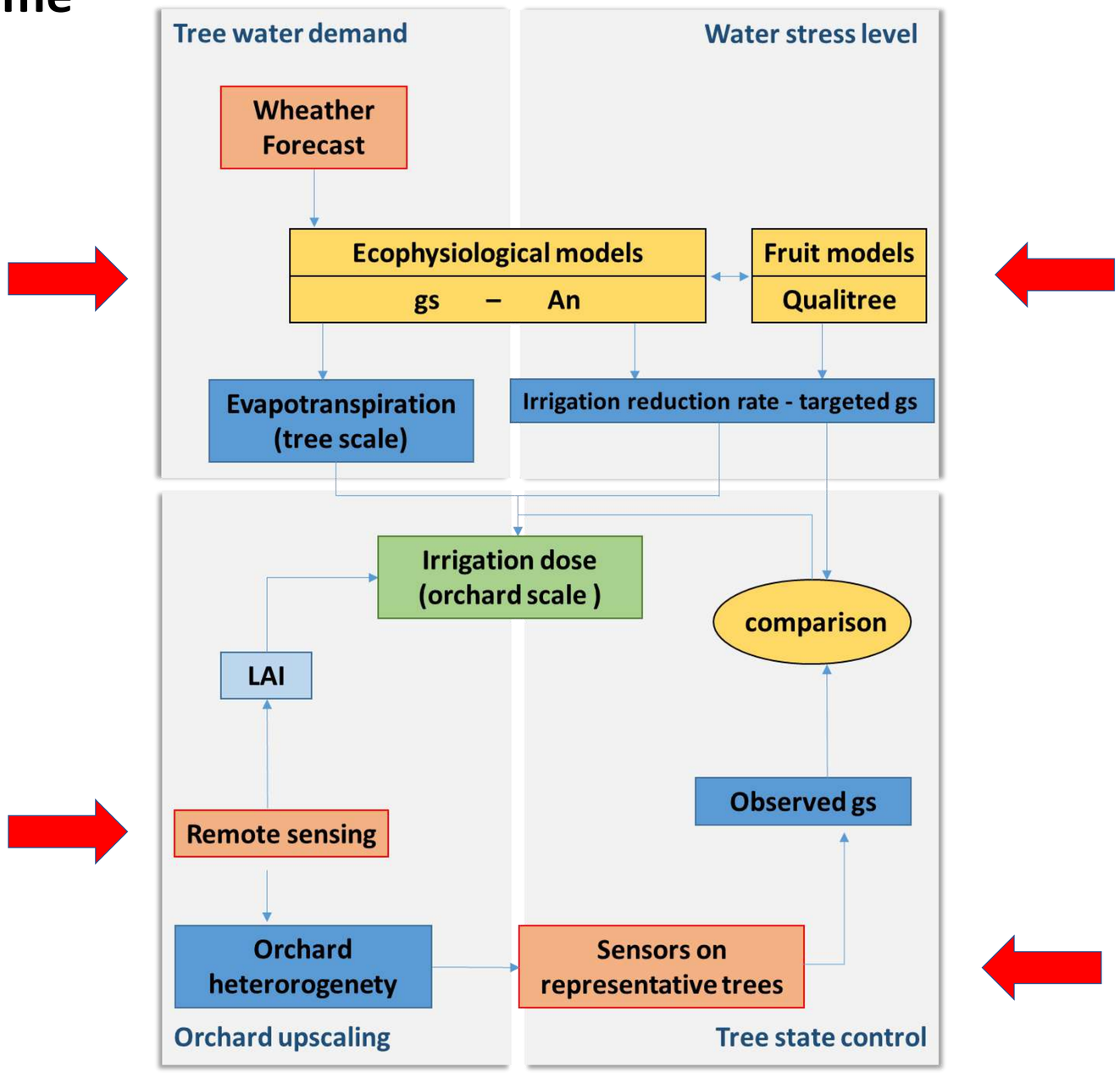


Figure 1. Scheme describing the main four modules of IRRIWELL.

Transpiration model

Penman-Monteith (1965)

$$\lambda E_p = A \frac{s(R_n - G) + \rho_a c_p VPD\, g_b}{s + \gamma(1 + g_b / g_c)}$$

Leaf area

Stomatal conductance

R_n= net radiation

G = soil heat flux

VPD = air vapour pressure deficit

ρ_a, c_p, s, γ= physical constants

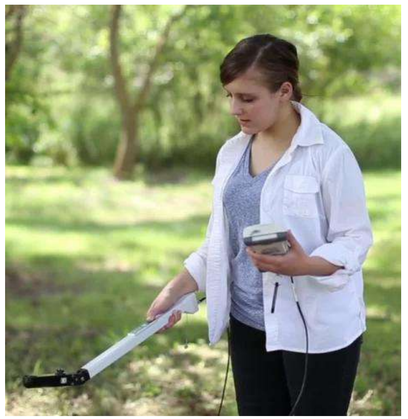
g_b, gc= aerodynamic and stomatal conductances

A = leaf area

LEAF AREA



Direct measurement



Indirect measurement

Stomatal conductance



IRGA/porometer

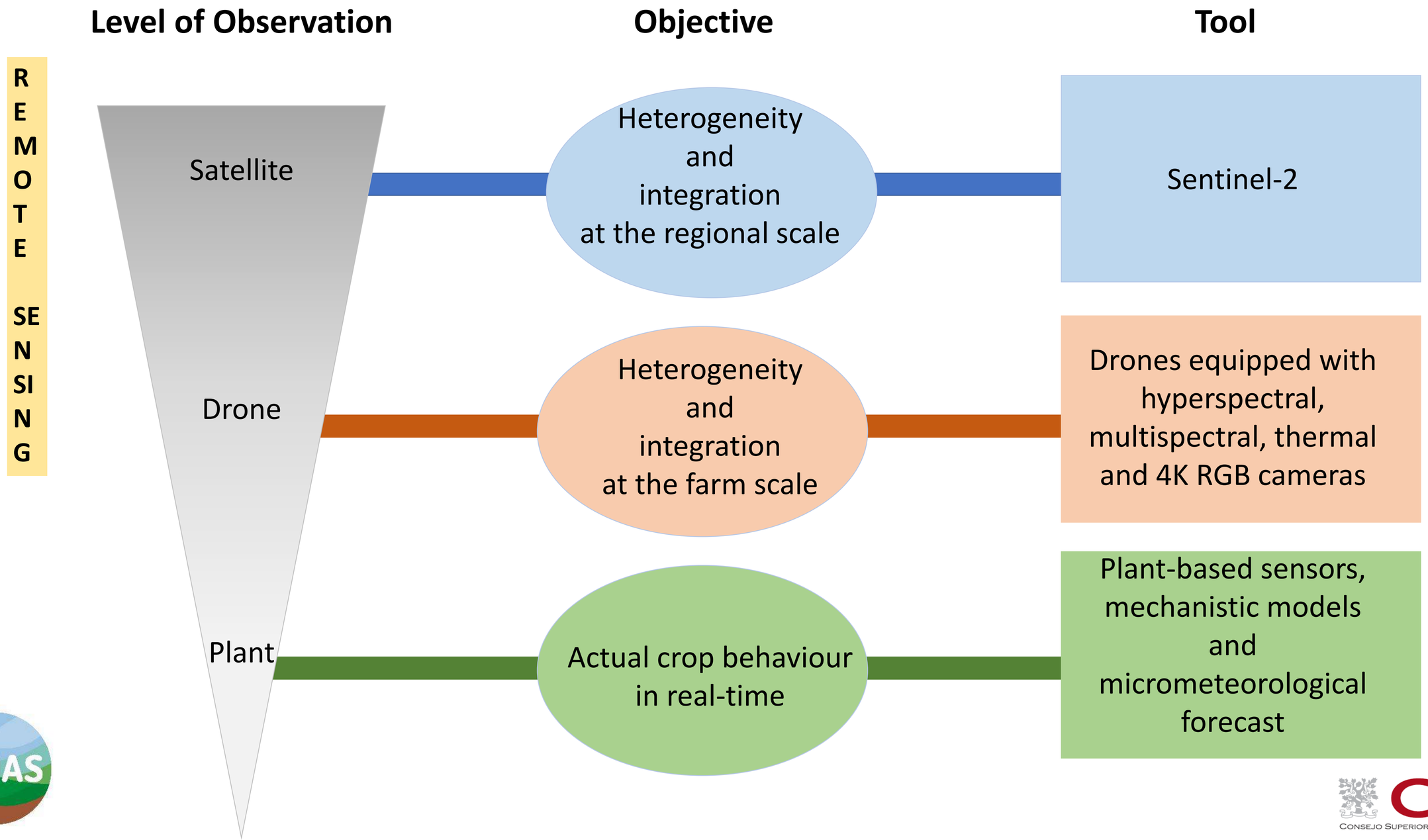




Sensor estimation

Leaf area estimation

Assessing the heterogeneity



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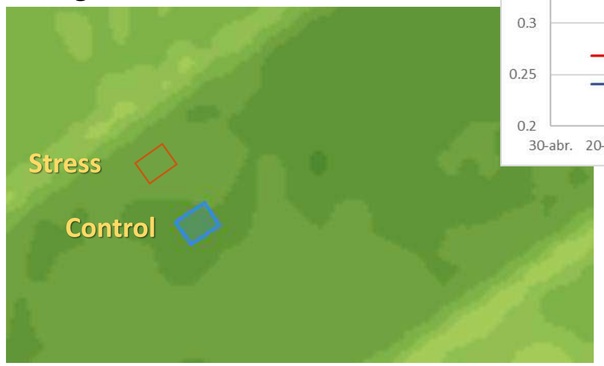
Assessing the heterogeneity

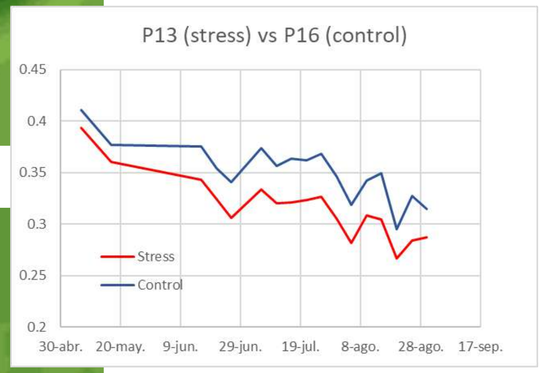
Sentinel-2 NDVI

2 May 2018

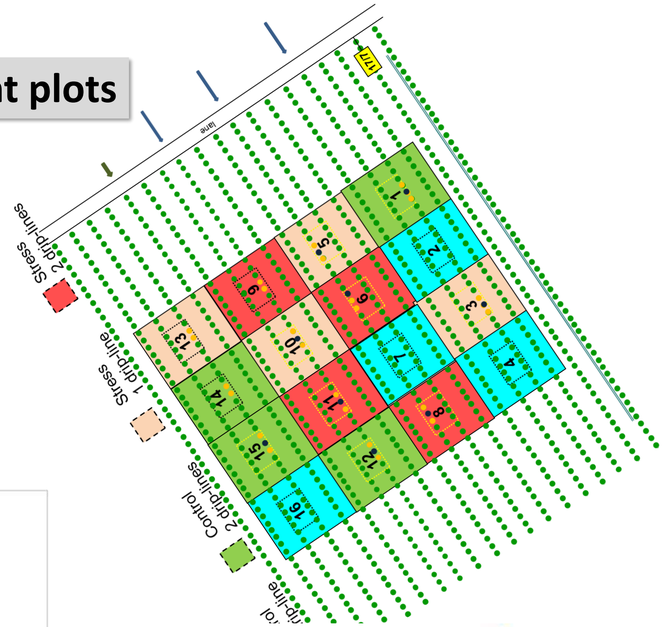


30 August 2018

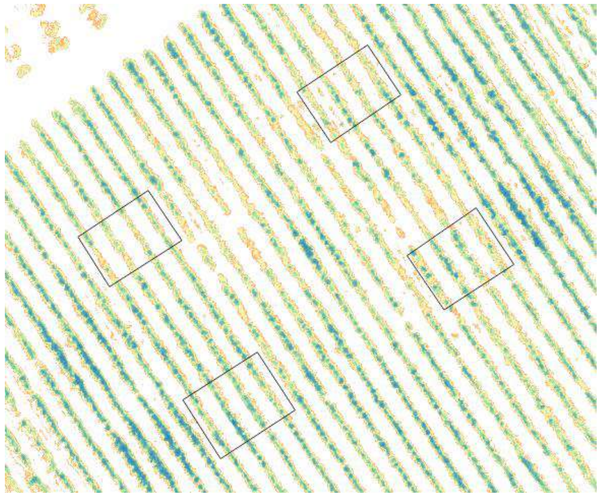


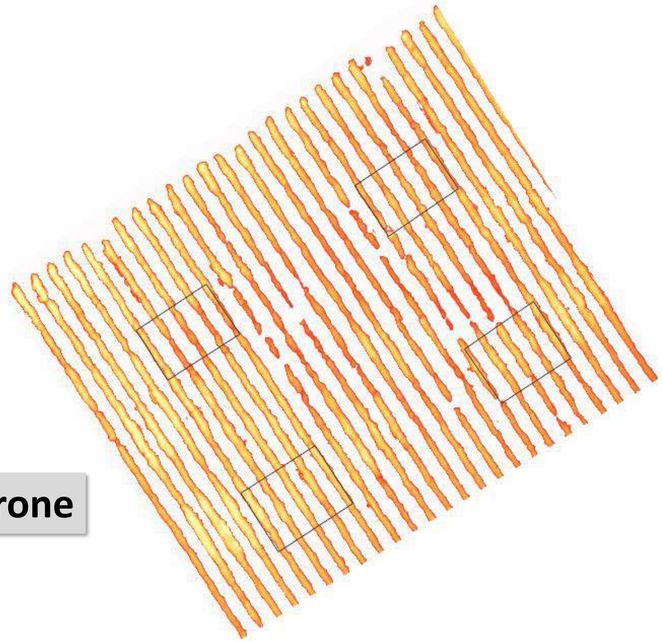


Treatment plots



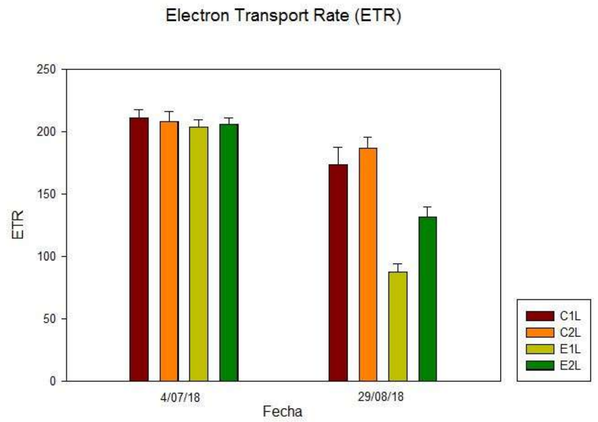
NDVI drone





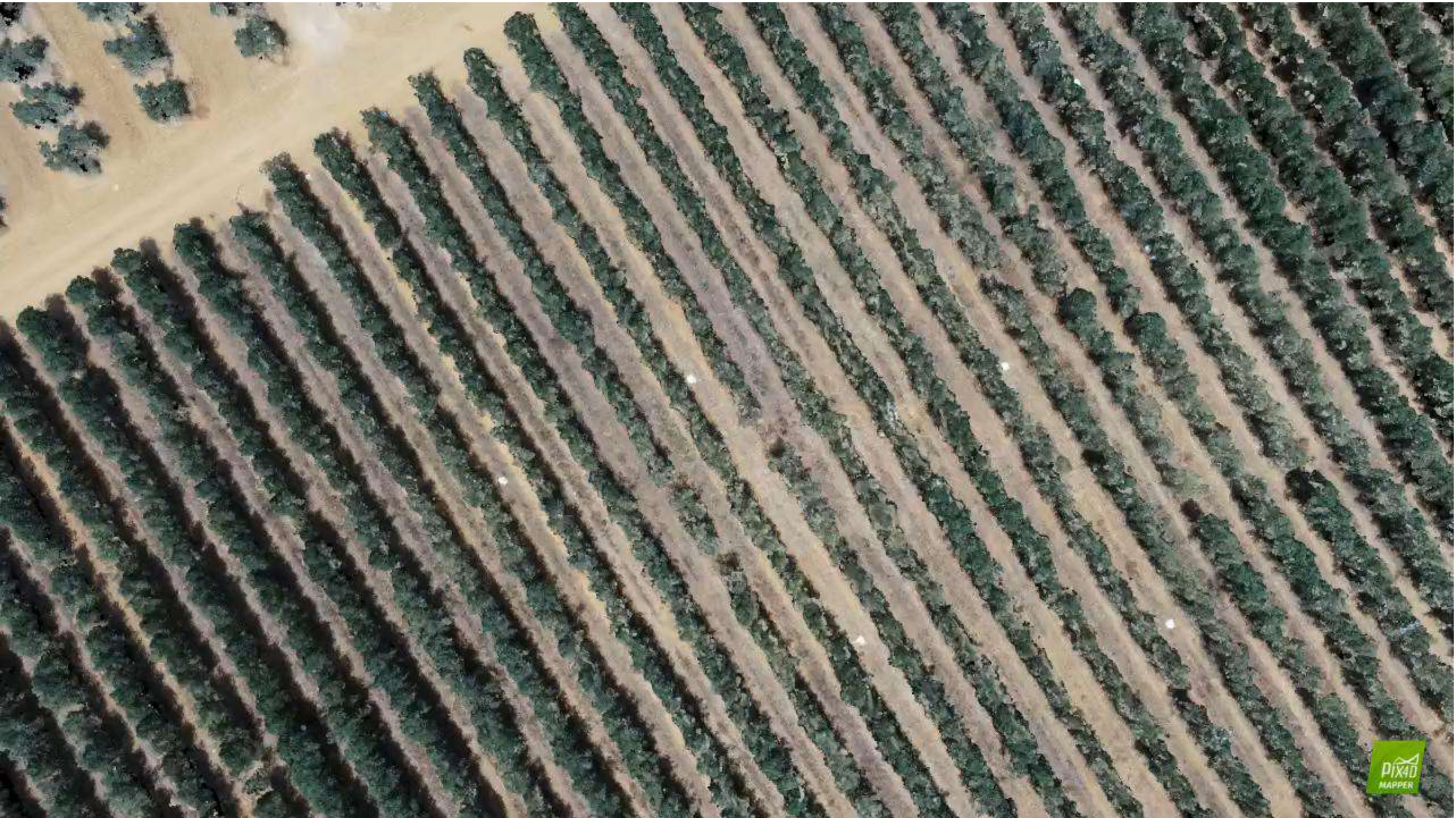
Thermal drone

Photosynthetic capacity (Licor 6400)



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PIX4D
MAPPER

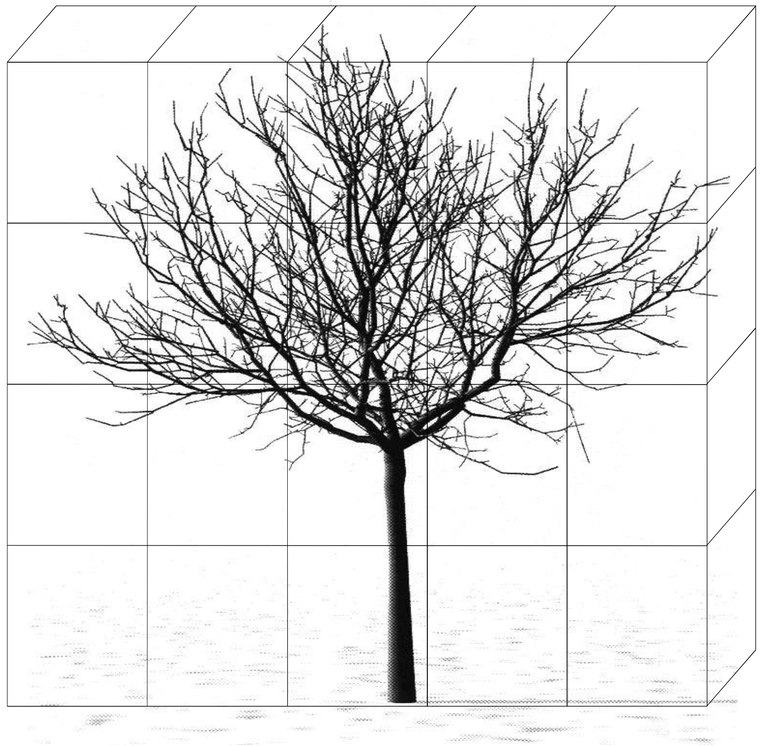






3D Radiation interception model (RATP model)

In each cell:

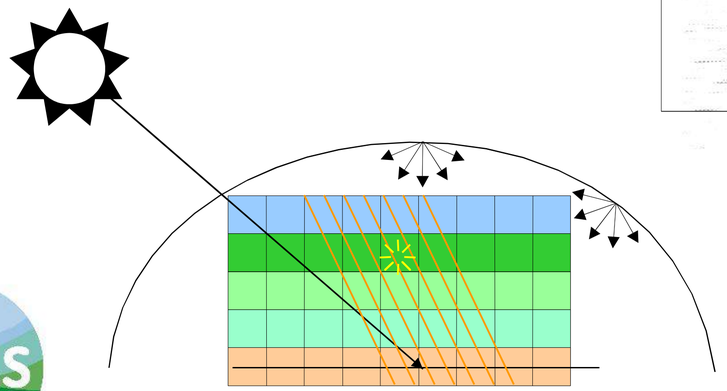


Structure and properties
***LAD*, inclinations,**
scattering coefficients

Radiation transfer
leaf irradiance
light regime

Energy balance
stomatal conductance
transpiration
leaf temperature

Photosynthesis
net CO_2 assimilation

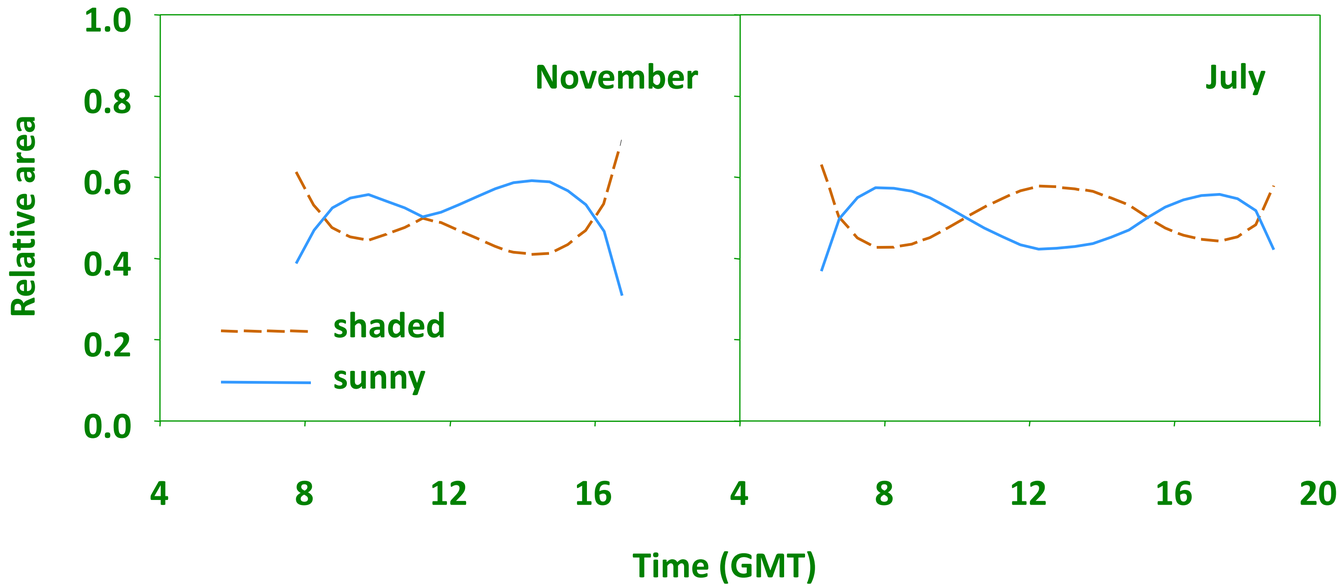


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RATP model outputs

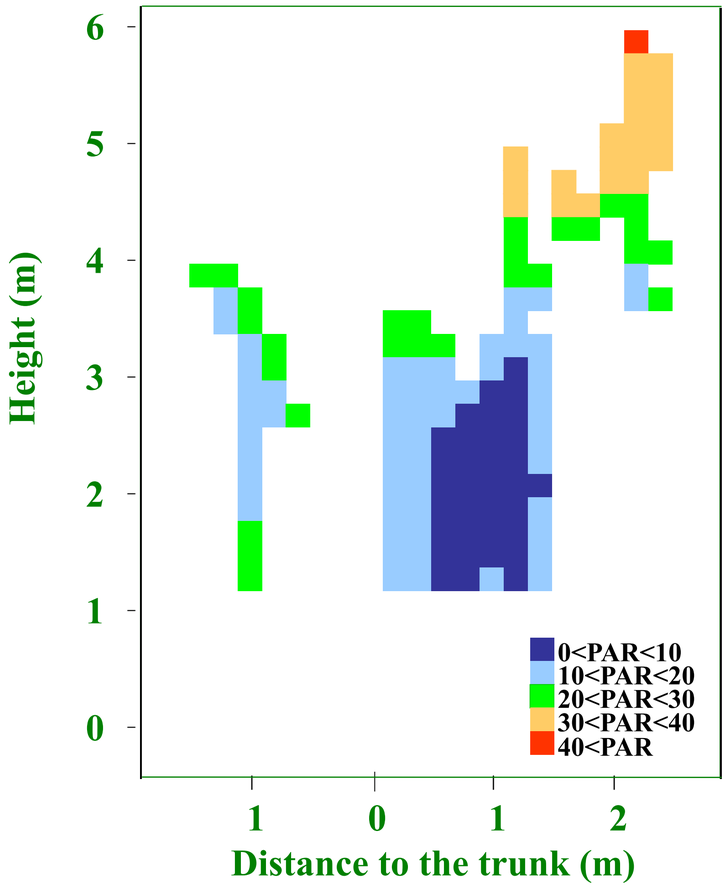
Sunny and shaded leaf area



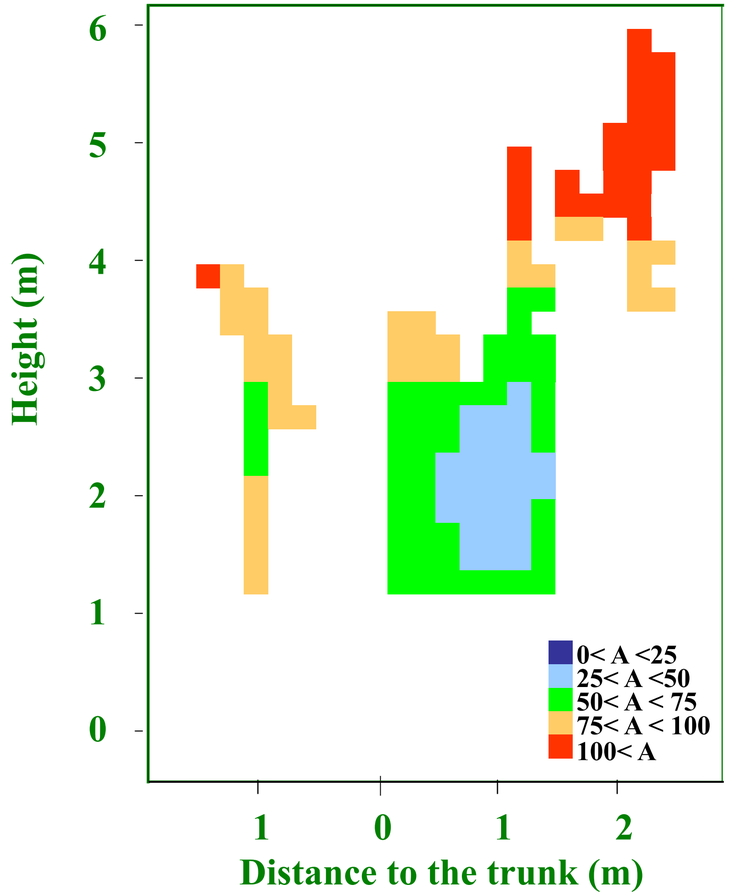
$$E_p = g_{s,sun} \cdot f(VPD) \cdot A_{sun} + g_{s,shade} \cdot f(VPD) \cdot A_{shade}$$

RATP model outputs

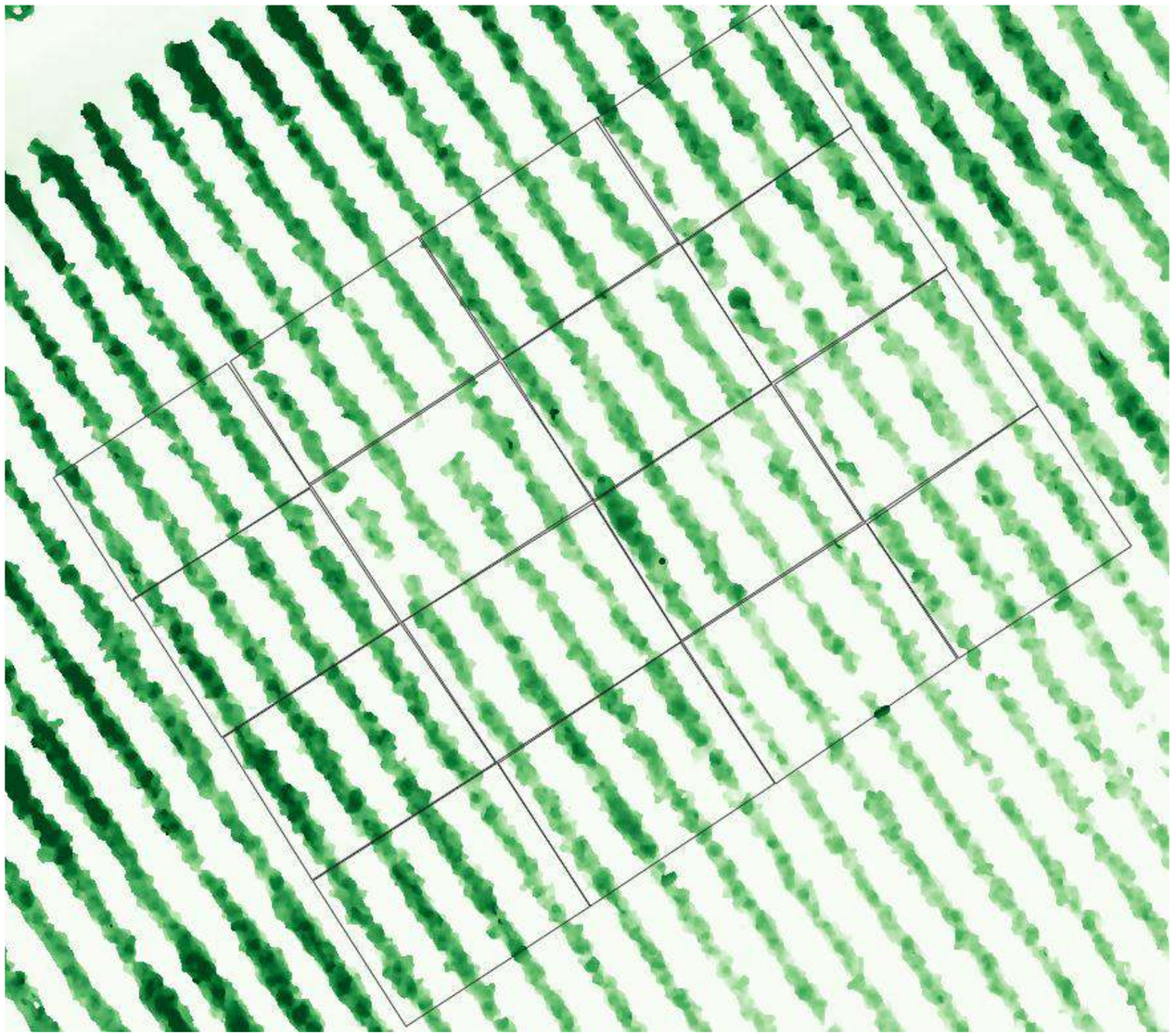
PAR distribution



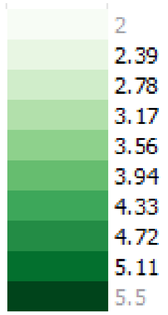
Photosynthesis distribution



Distribution of tree heights



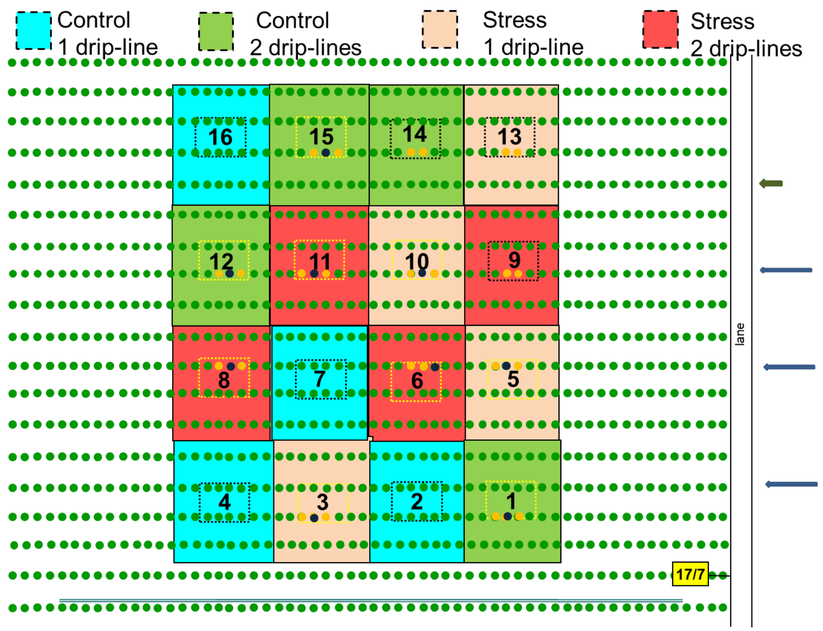
Height (m)

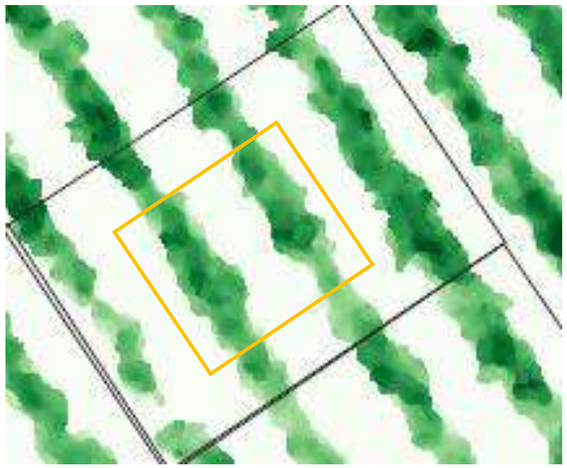


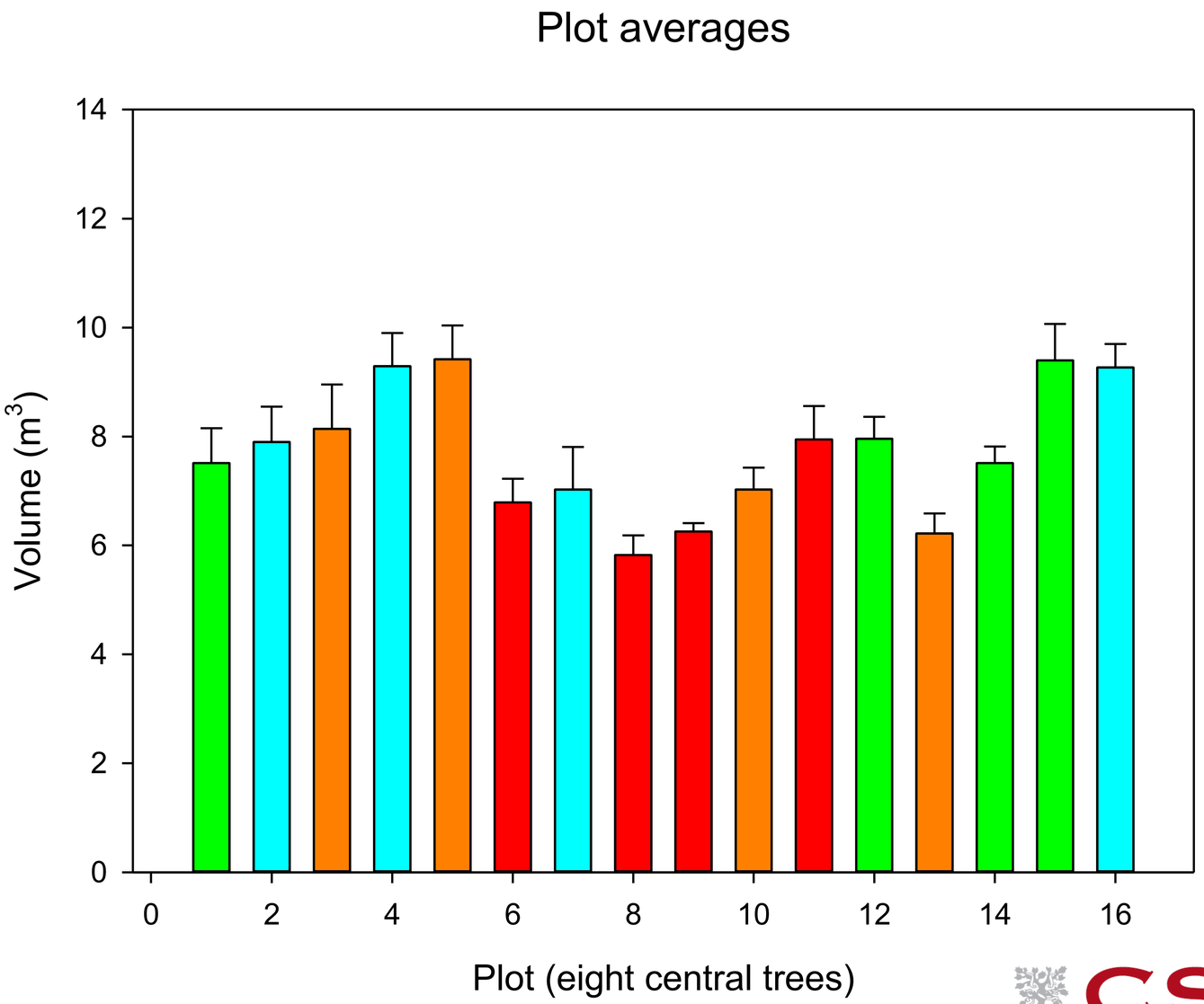
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A tool to manage heterogeneity





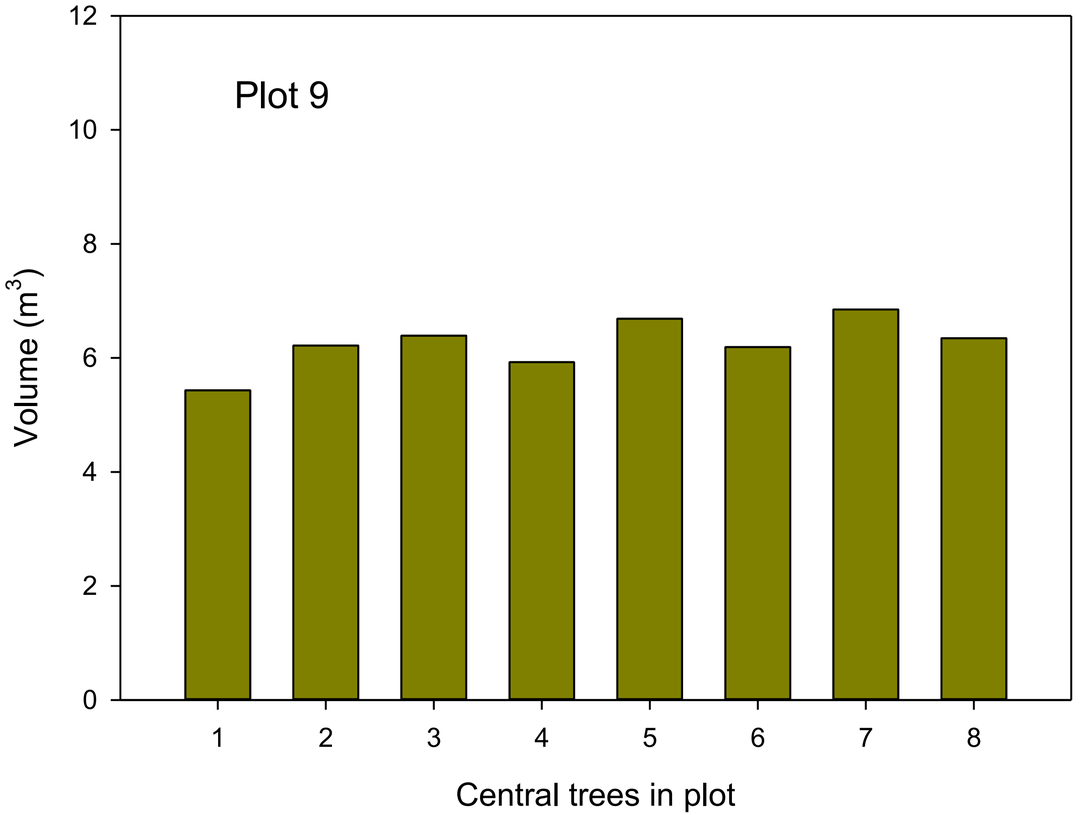


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A tool to manage heterogeneity

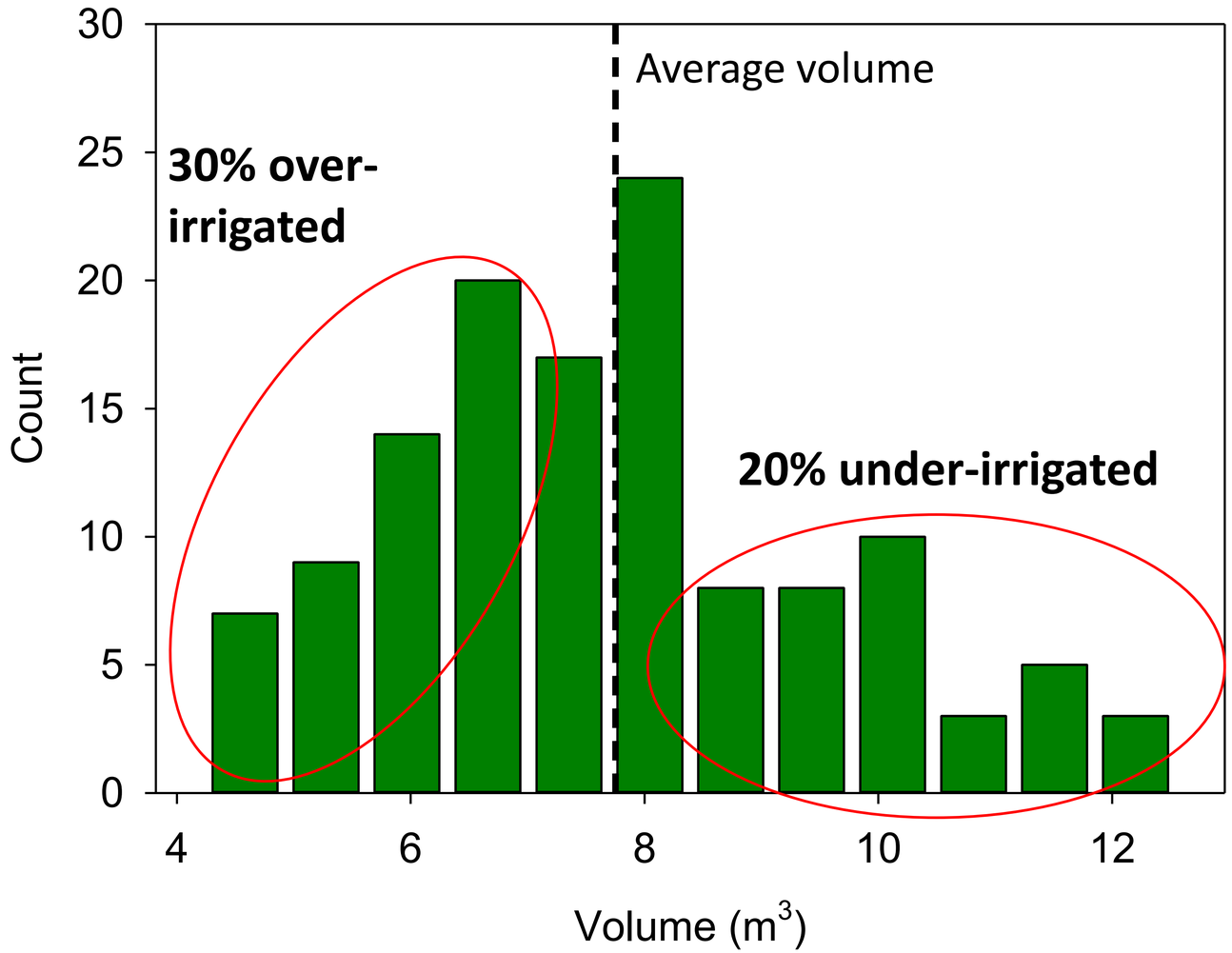




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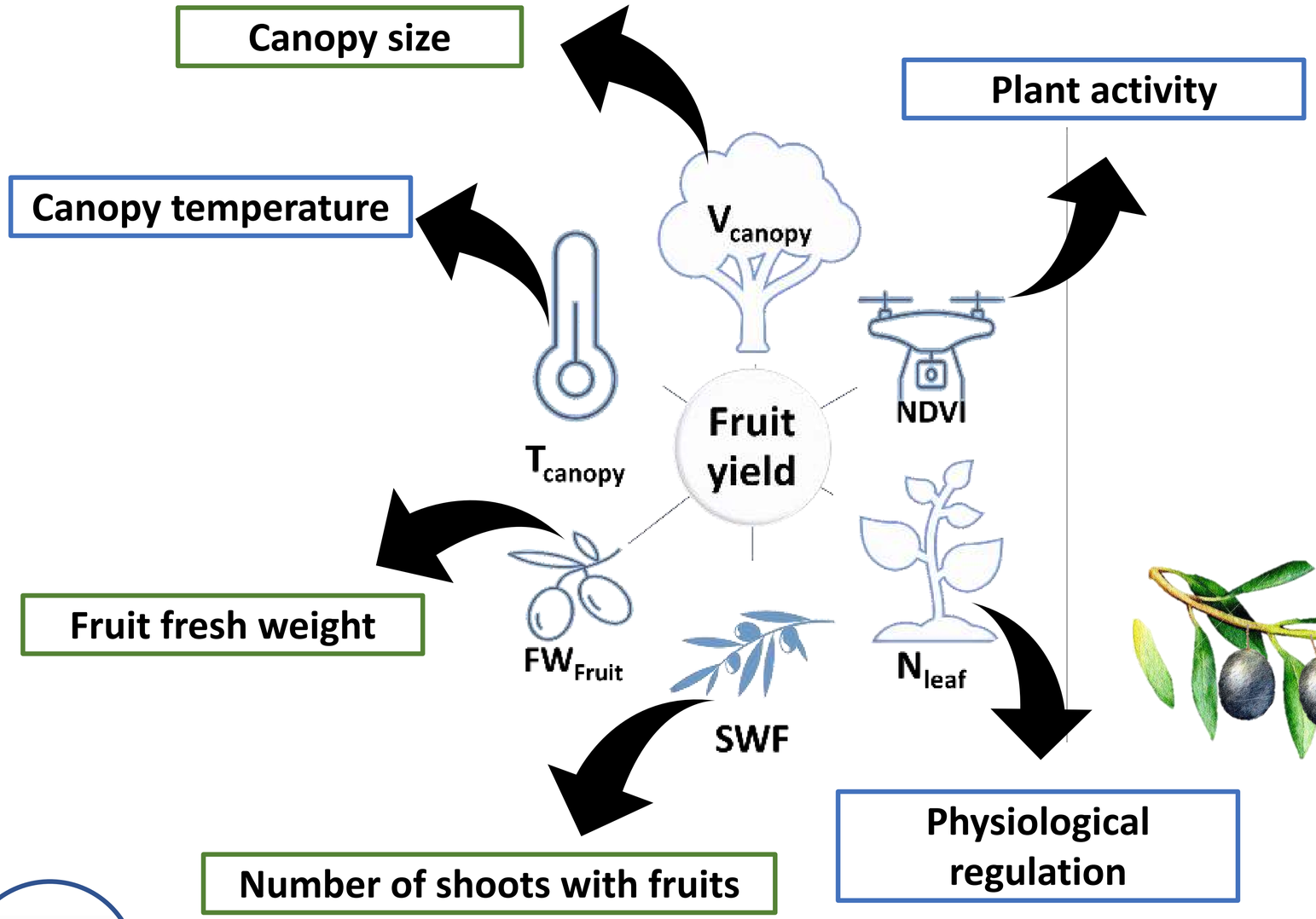
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A tool to manage heterogeneity



2. Digital models of canopy size impact olive yield

What factors are involved?







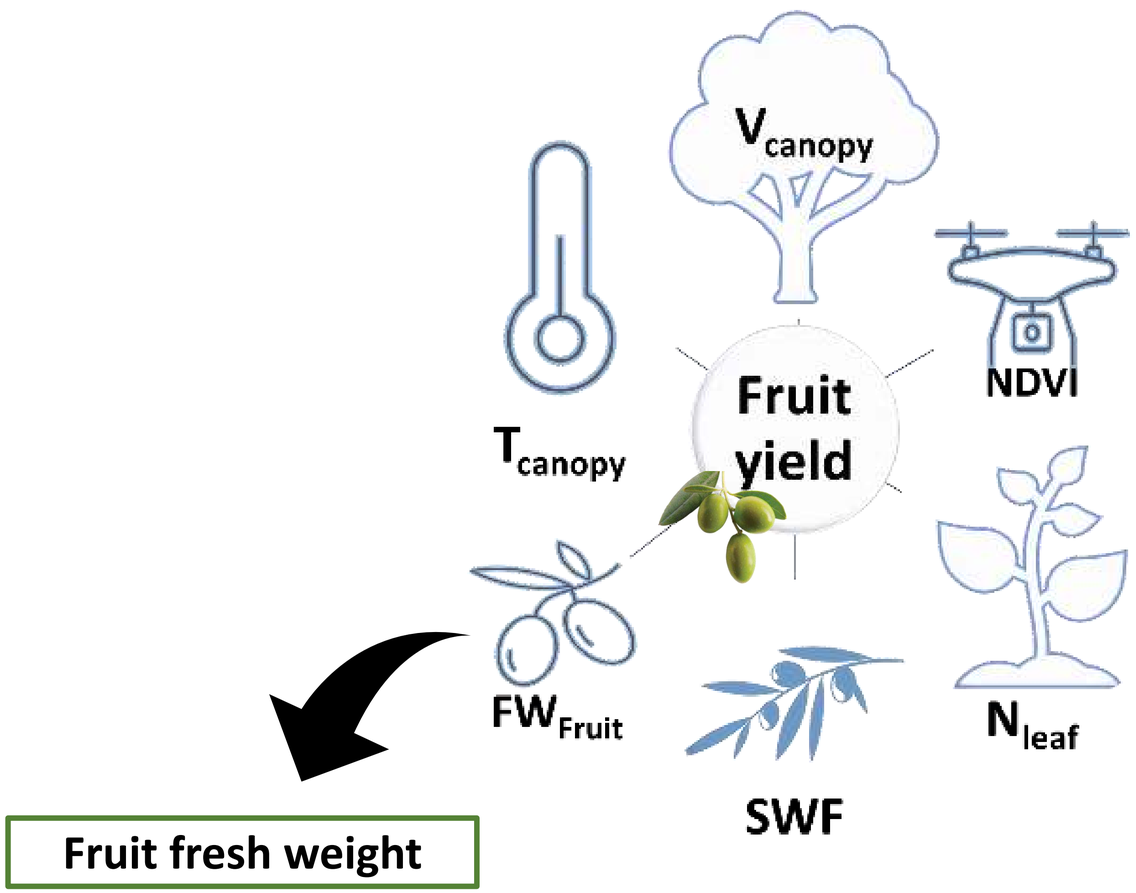


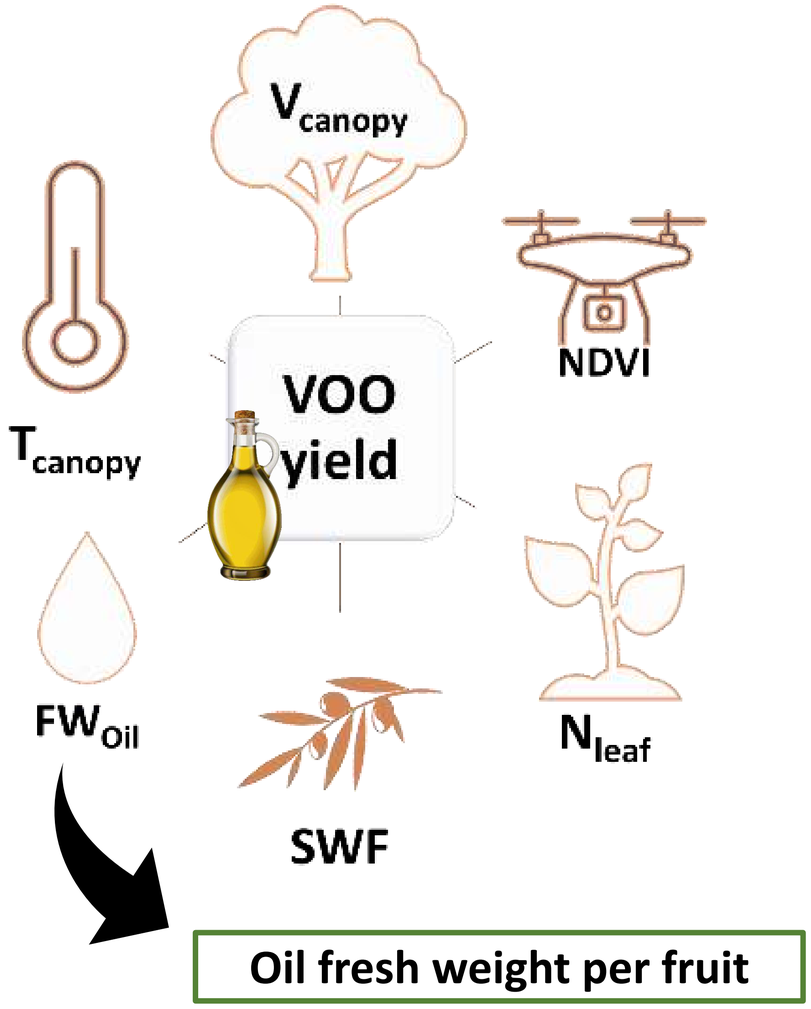


2.

Digital models of canopy size impact olive yield

What factors are involved?

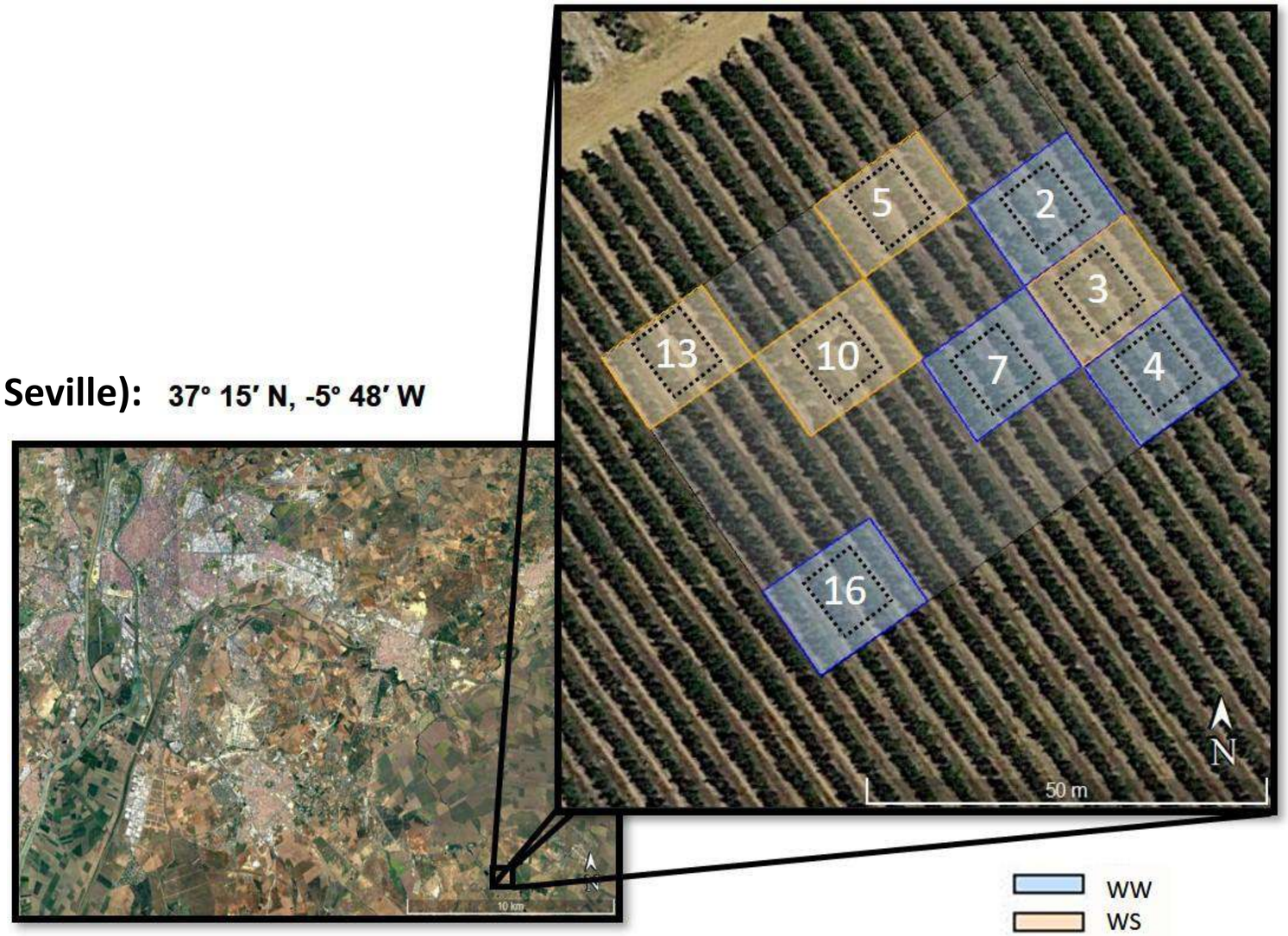






2. Digital models of canopy size impact olive yield

Utrera (South of Seville): 37° 15′ N, -5° 48′ W



WW TREES

WS TREES

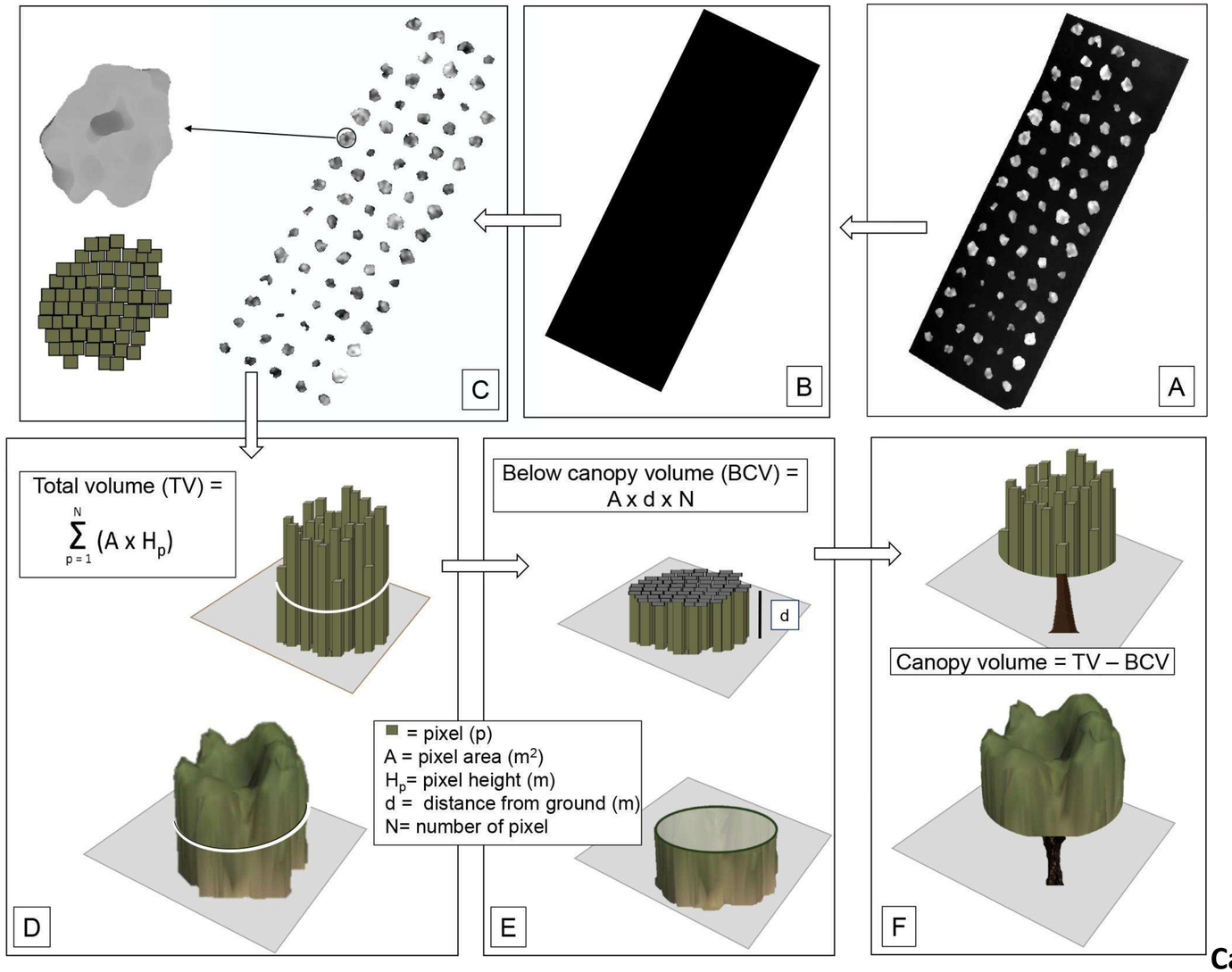


2. Digital models of canopy size impact olive yield



Digital Surface Models (DSM)

Digital Terrain Models (DTM)



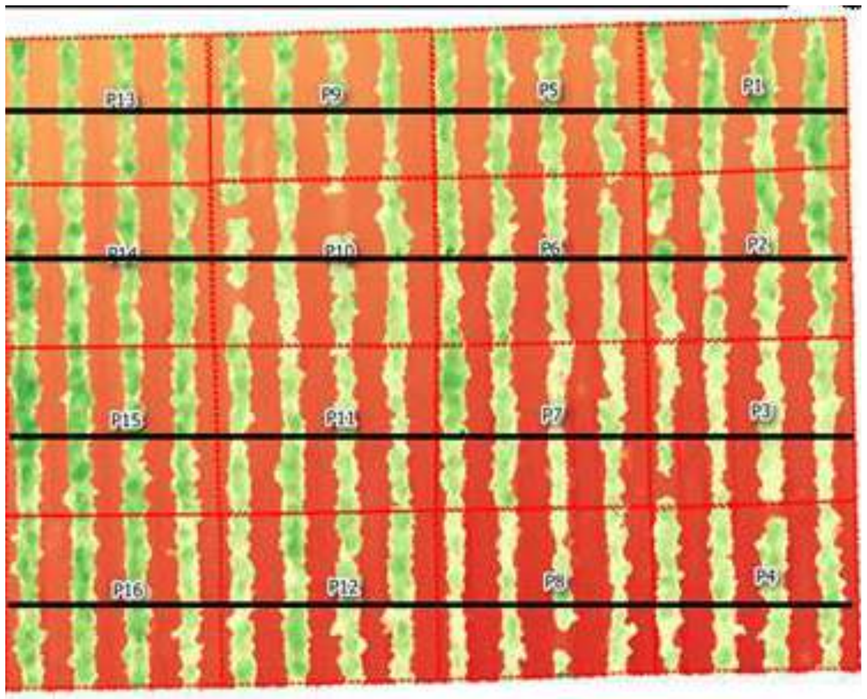
Caruso et al. 2019



2. Digital models of canopy size impact olive yield

Estimation of canopy volumes from UAV







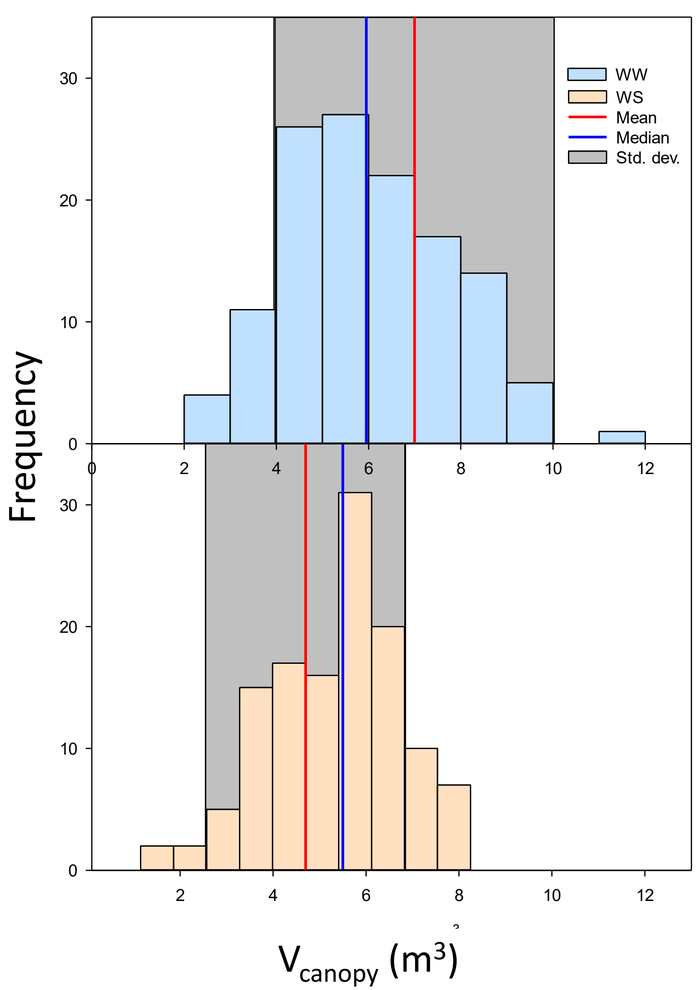
Spacial distribution of canopy heights

Calculation of tree volumes



2. Digital models of canopy size impact olive yield

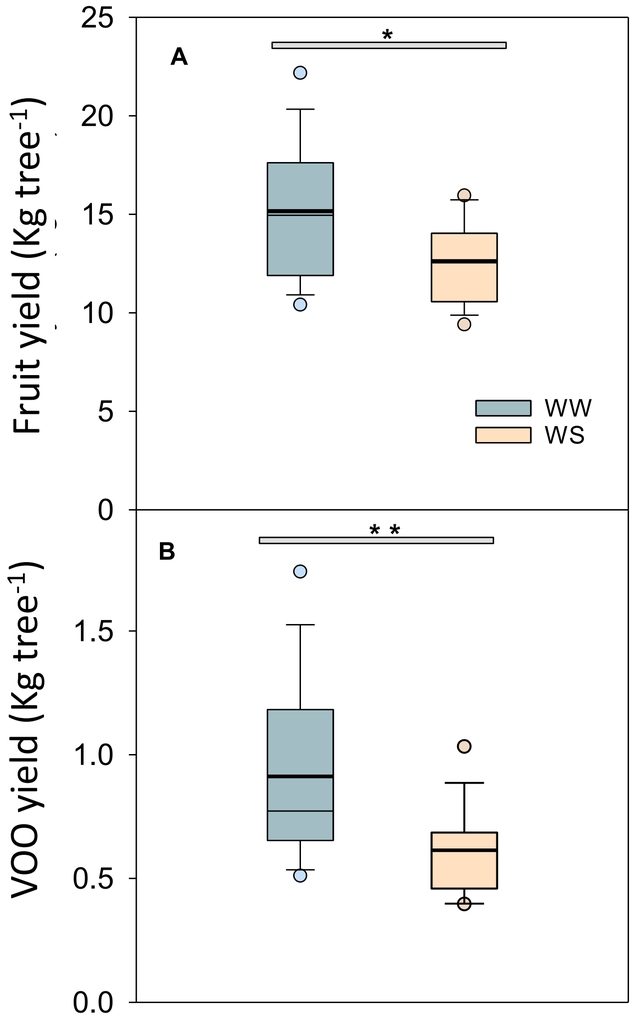
Canopy size distribution



WW TREES

WS TREES

Fruit and VOO yield







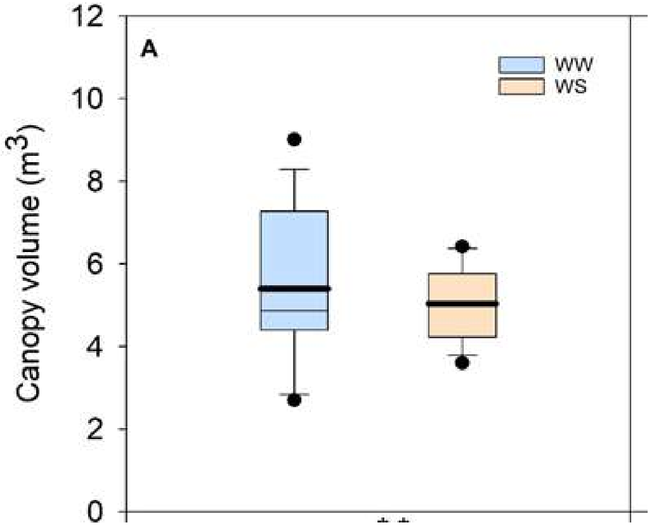


Tree-plot scale | Agronomy

2. Digital models of canopy size impact olive yield

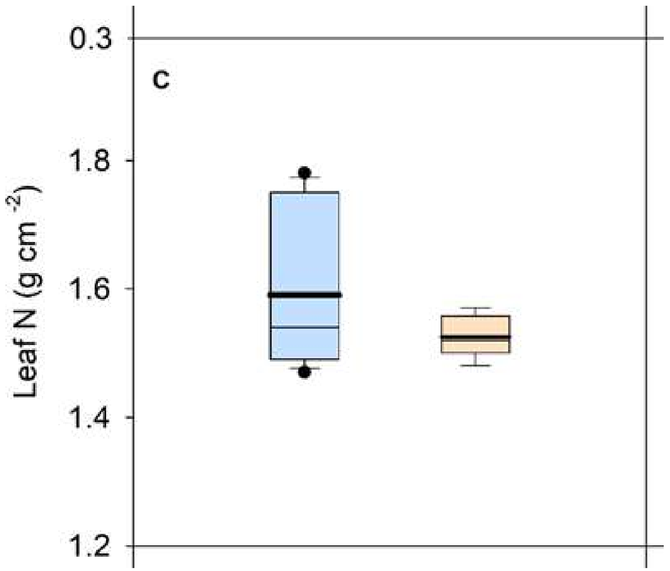


Canopy size



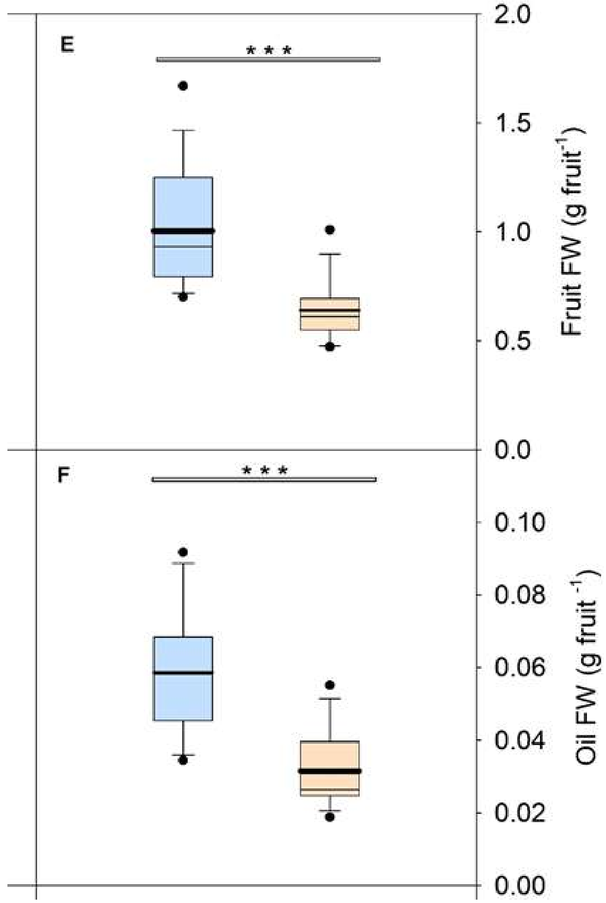


Leaf N Kjeldahl

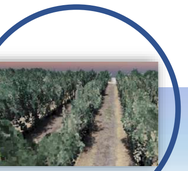


Fruit and VOO FW









Tree-plot scale | Agronomy

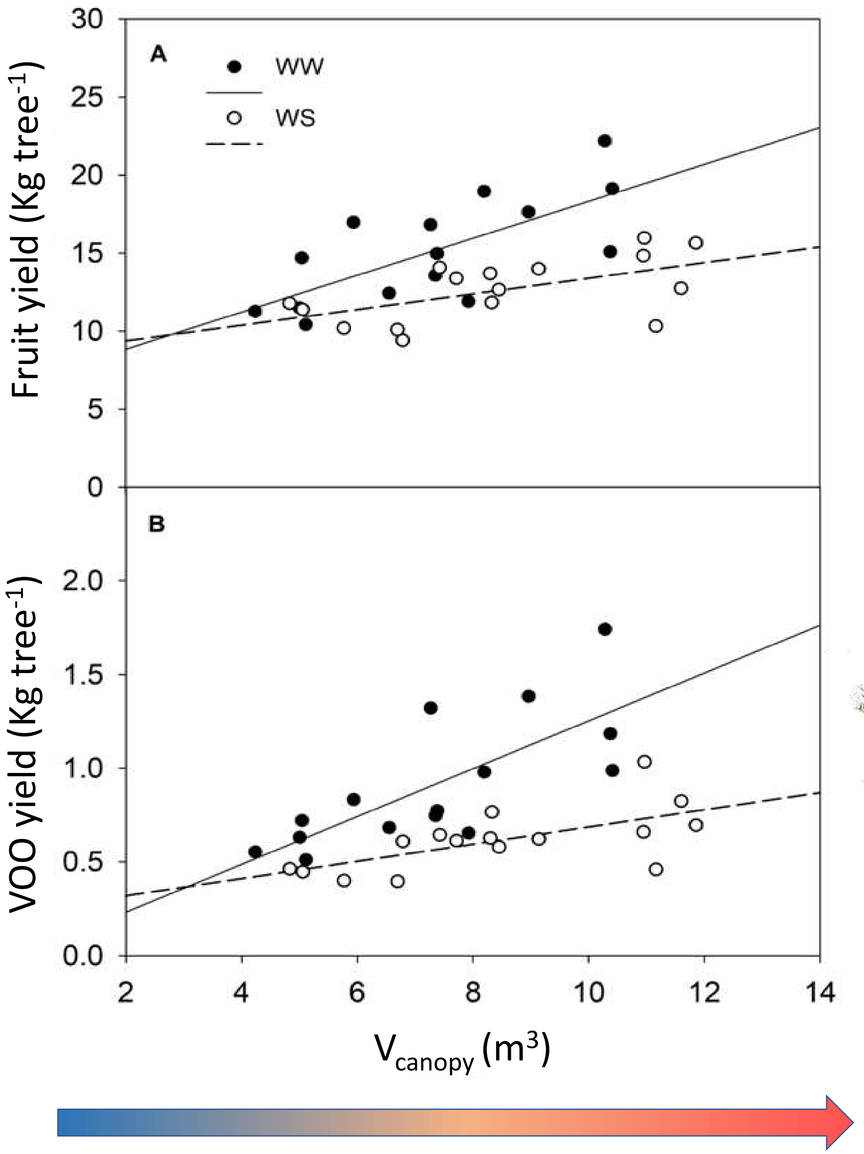
2.

Digital models of canopy size impact olive yield













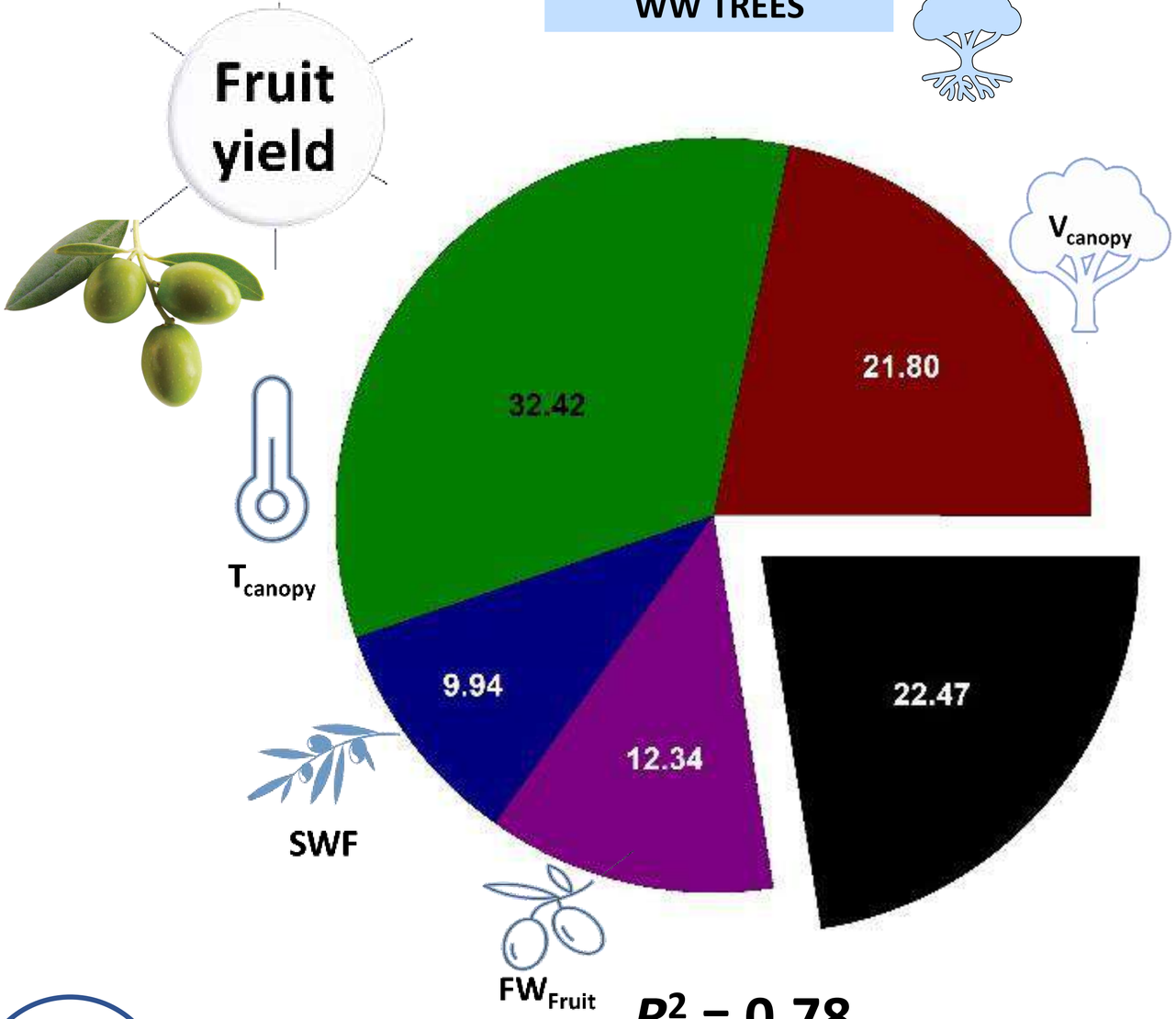
Tree-plot scale | Agronomy

2. Digital models of canopy size impact olive yield



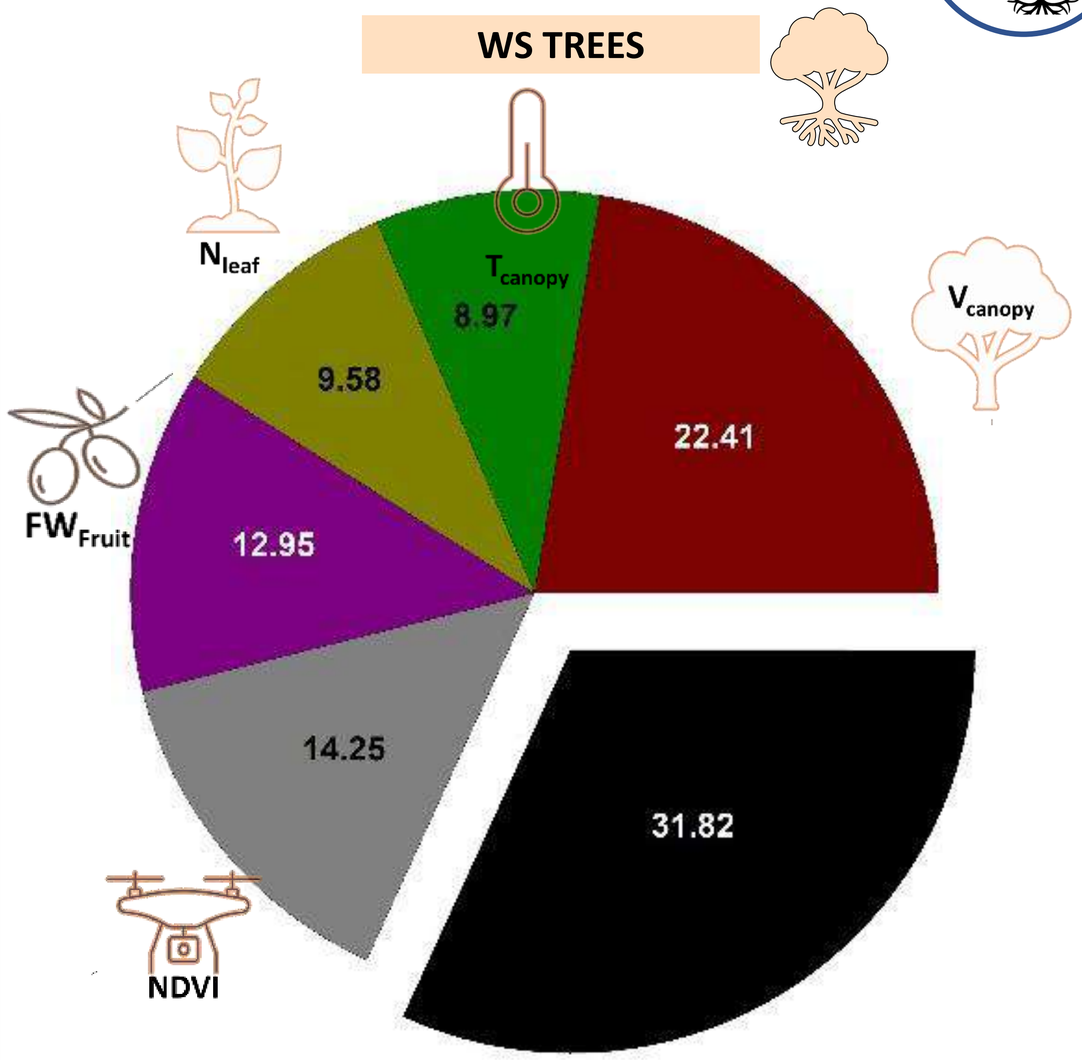


WW TREES



$R^2 = 0.78$

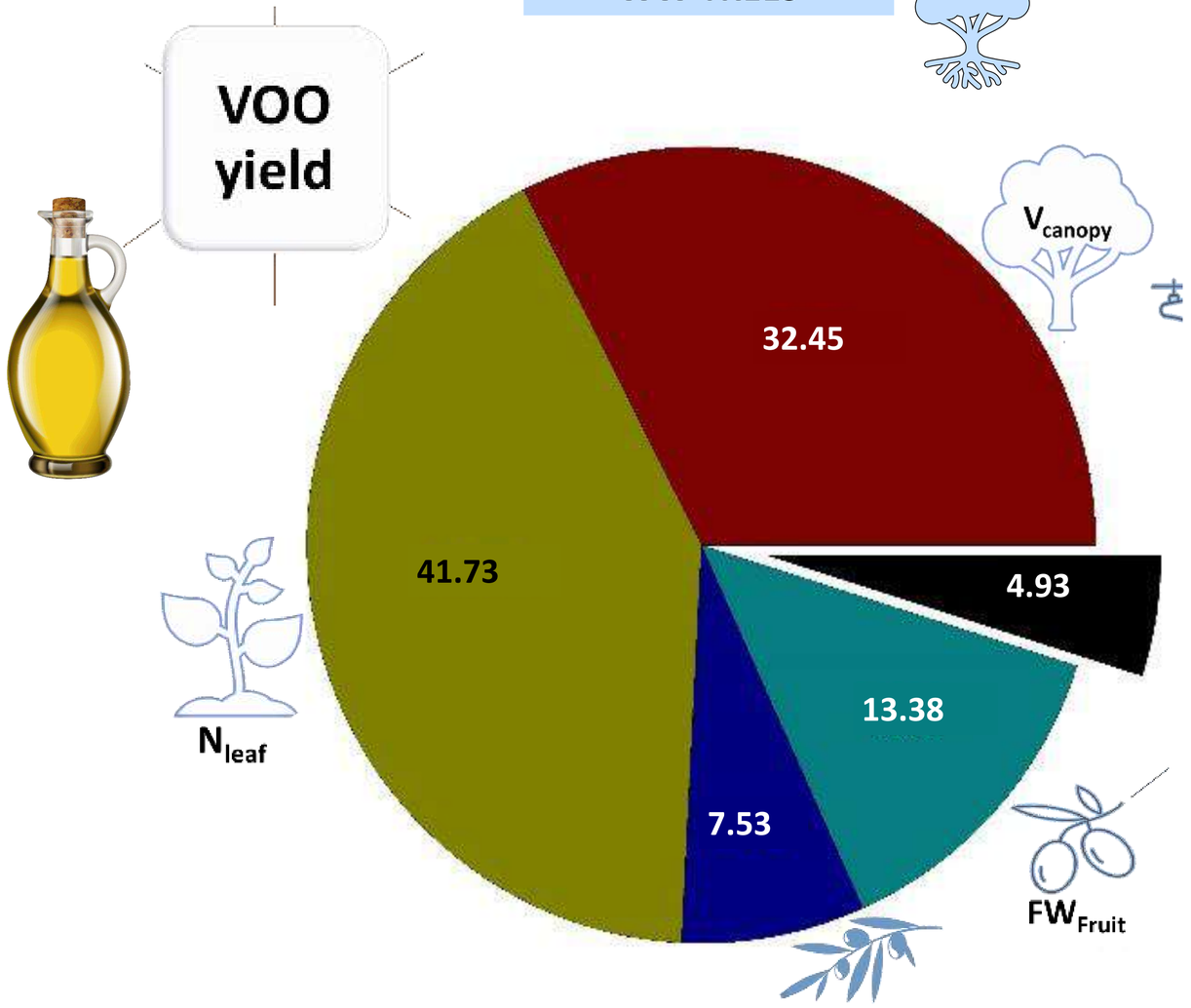
WS TREES



$R^2 = 0.68$

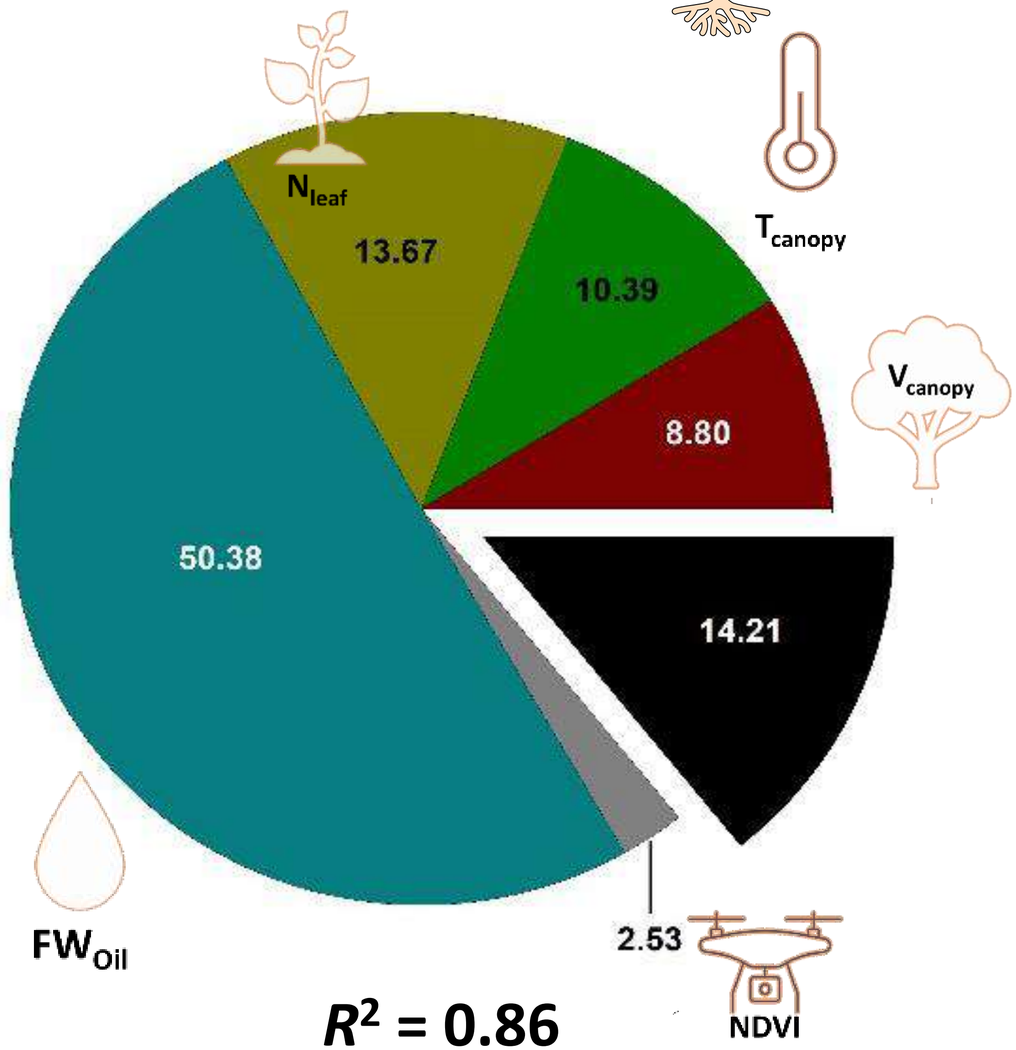
2. Digital models of canopy size impact olive yield

WW TREES



$R^2 = 0.95$

WS TREES



$R^2 = 0.86$



Tree-plot scale | Agronomy

LEAF AREA

Leaf area = cover x LAI

Cover (proyected)

Dron

Poligons

LAI

LAI-2200C

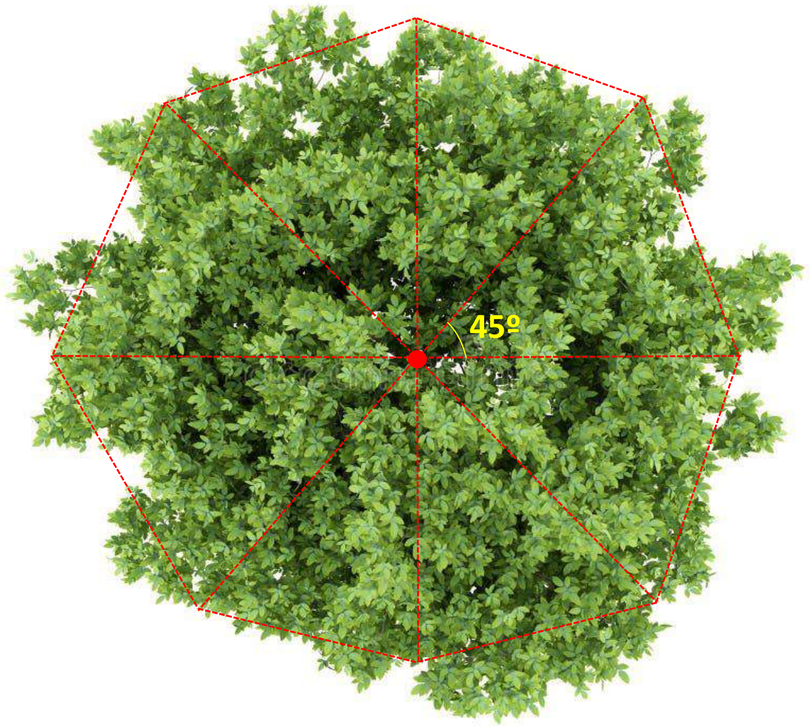
Viticanopy

Destructive method for leaf area determination

LEAF AREA

Cover

Poligons



Dron





MATERIALES Y MÉTODOS

LAI

LAI-2200C



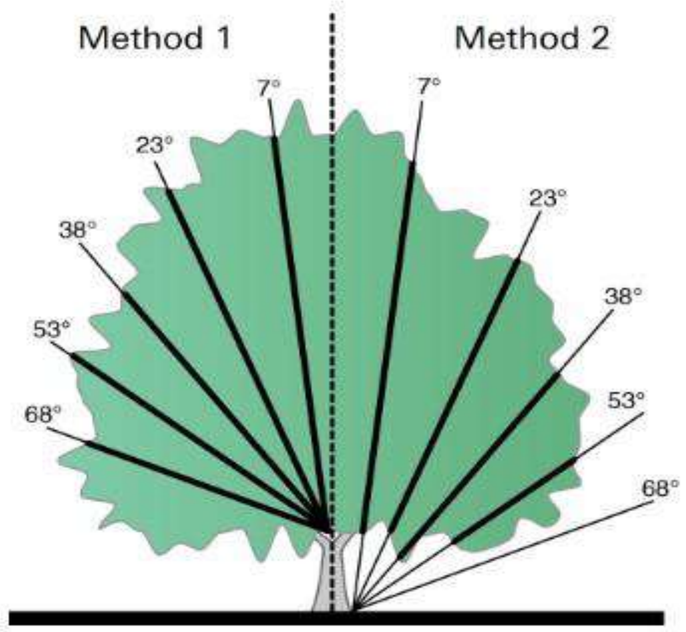
Viticanopy



LEAF AREA

LAI (individual)

LAI-2200C



Viticanopy



LEAF AREA

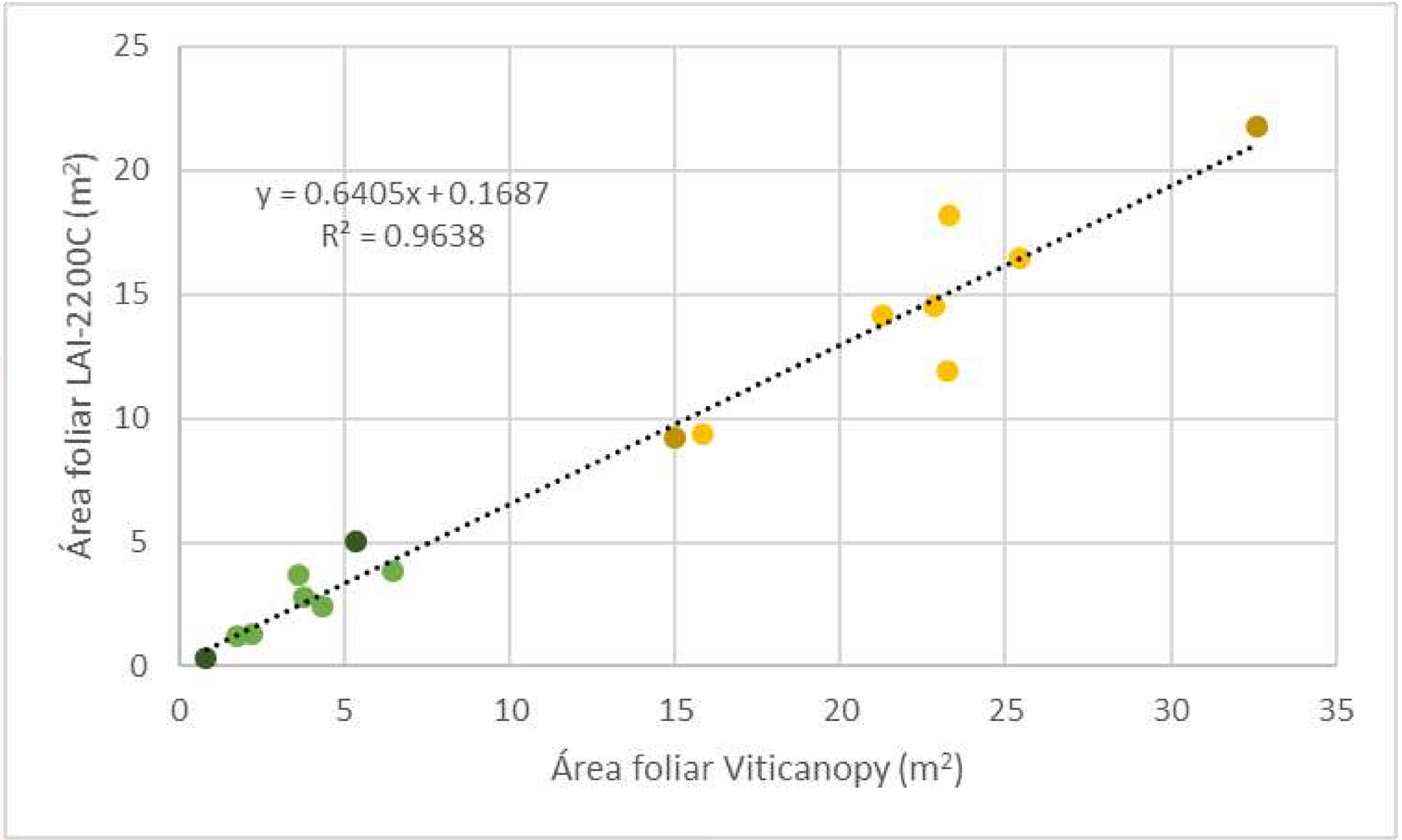
Destructive method





RESULTS

METHODS COMPARISON



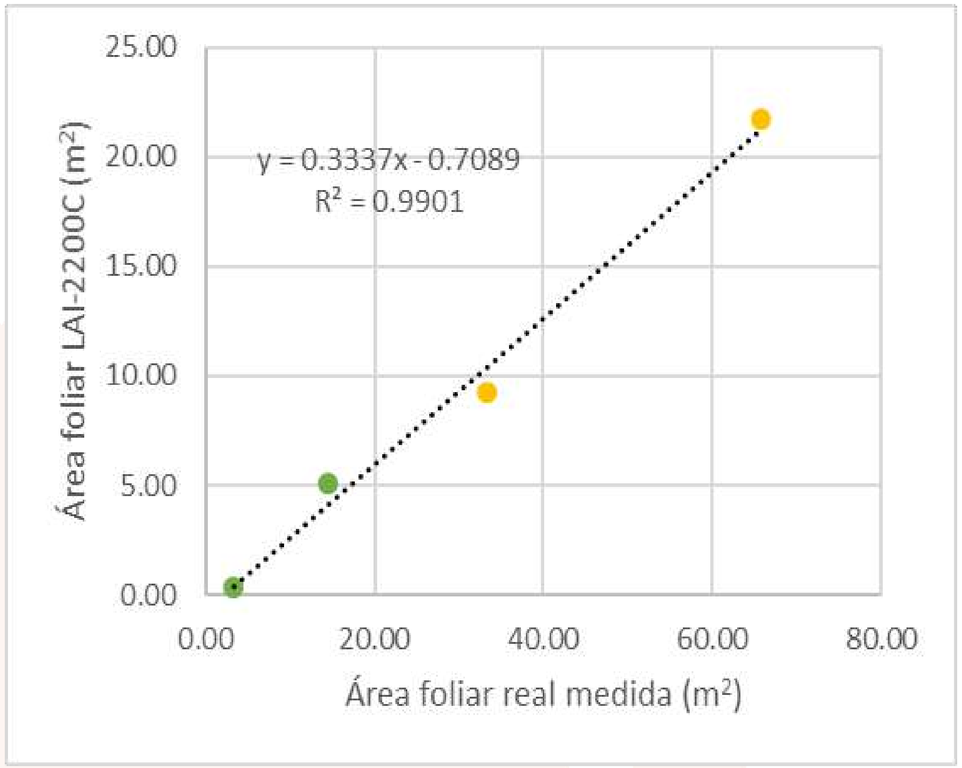
- Olivo
- Limonero
- Limonero Calibrado
- Olivo Calibrado

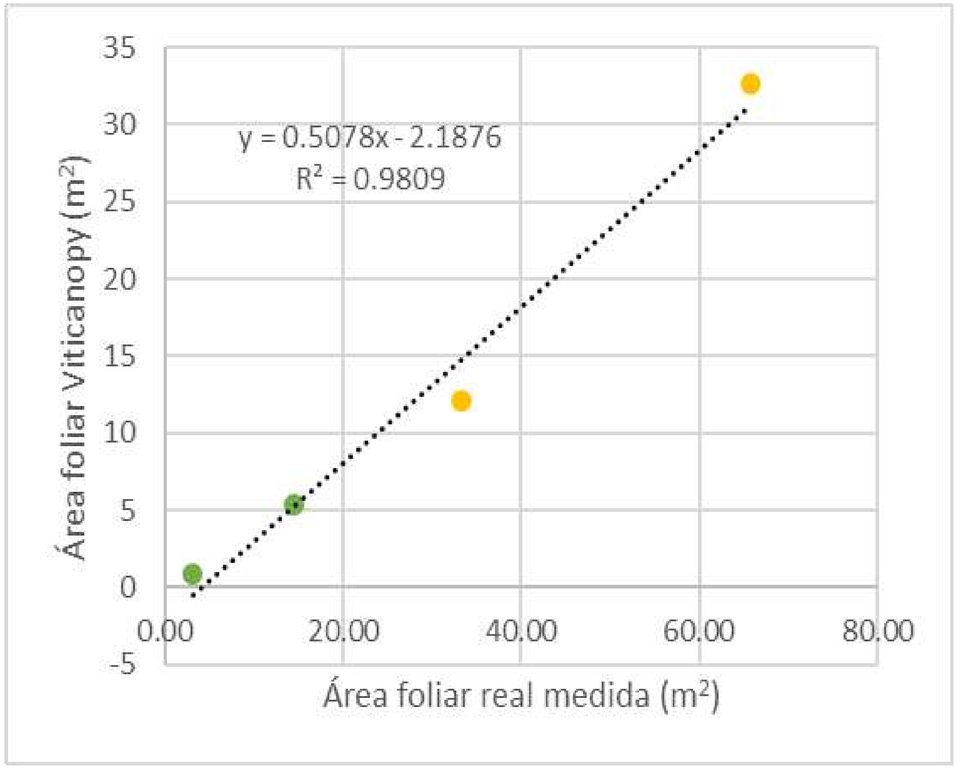
UNIVERSIDAD PABLO DE OLAVIDE SEVILLA

RESULTS

ÁRBOLES INDIVIDUALES

METHOD VALIDATION





Olivo

Limonero

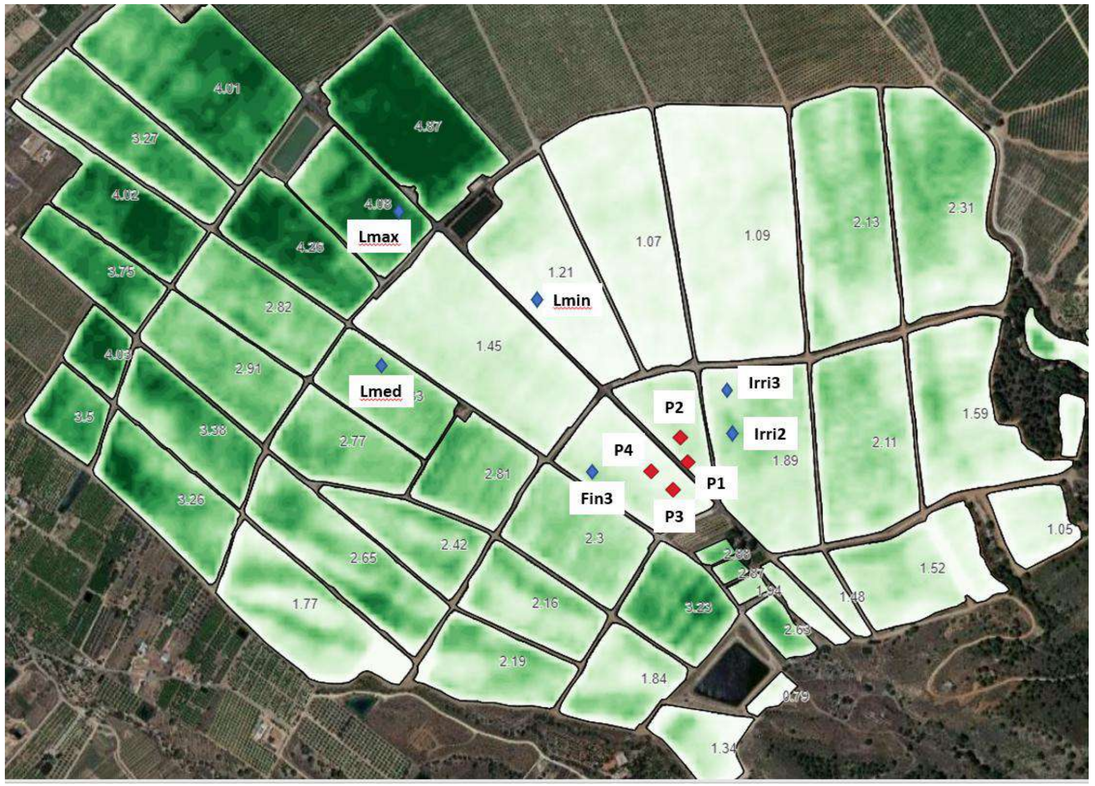
UNIVERSIDAD PABLO DE OLAVIDE SEVILLA

RESULTS

APLICACIÓN FINCA COMERCIAL

FINCA MUNDOSOL (MURCIA)

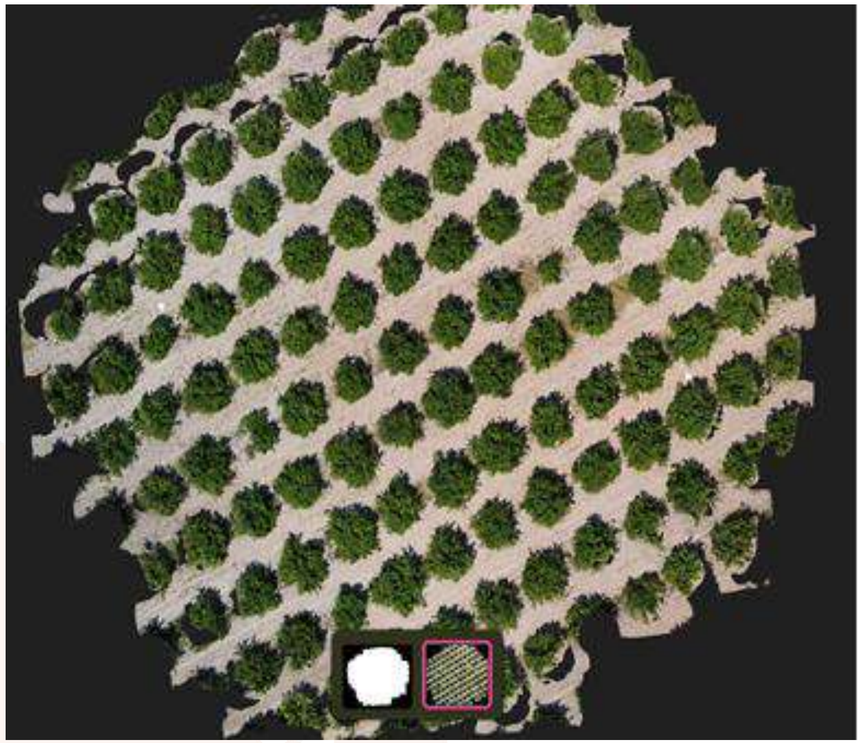


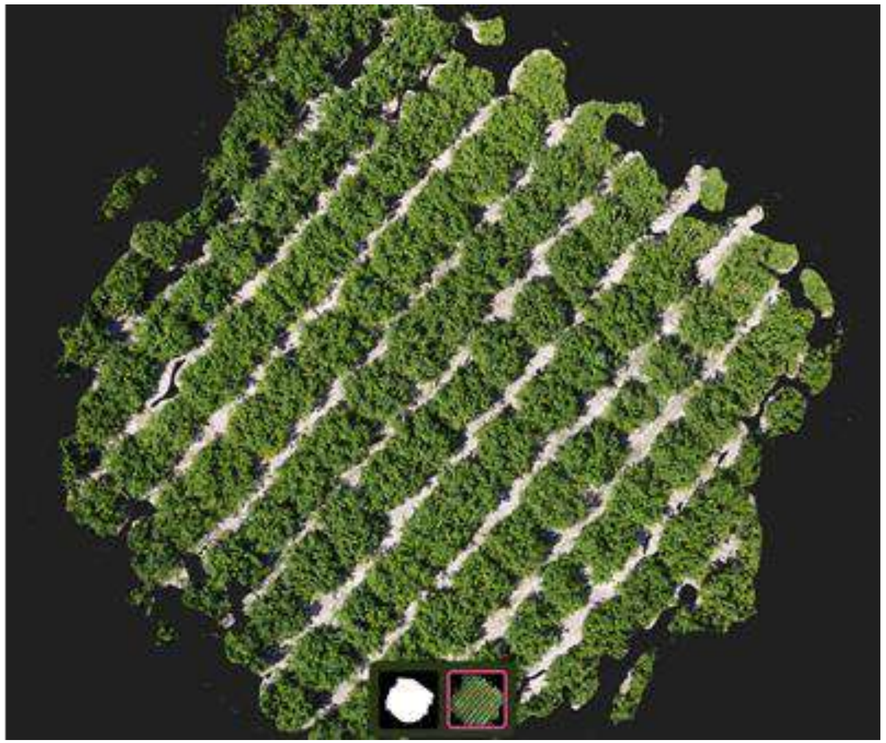


RESULTS

APLICACIÓN FINCA COMERCIAL

ESTIMACIÓN COBERTURA CON DRON

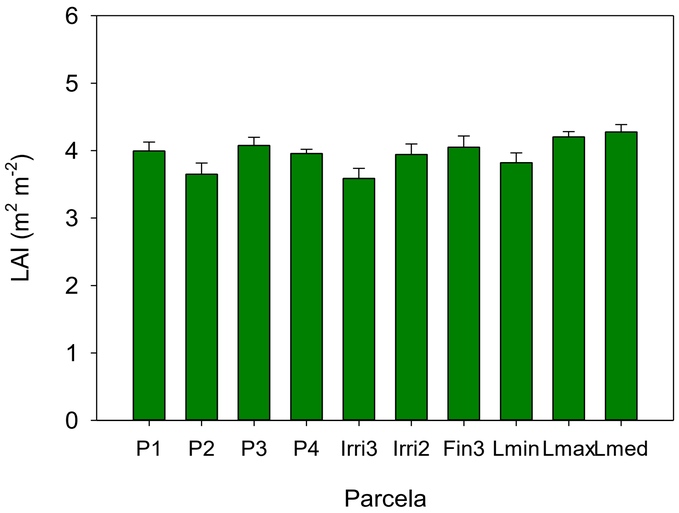


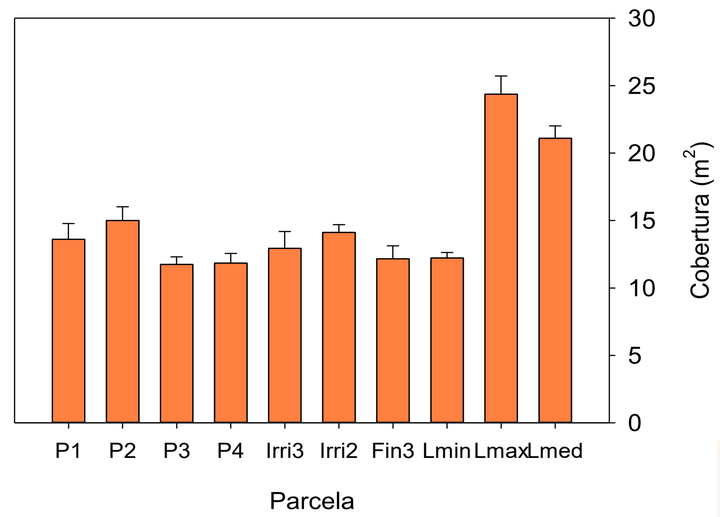


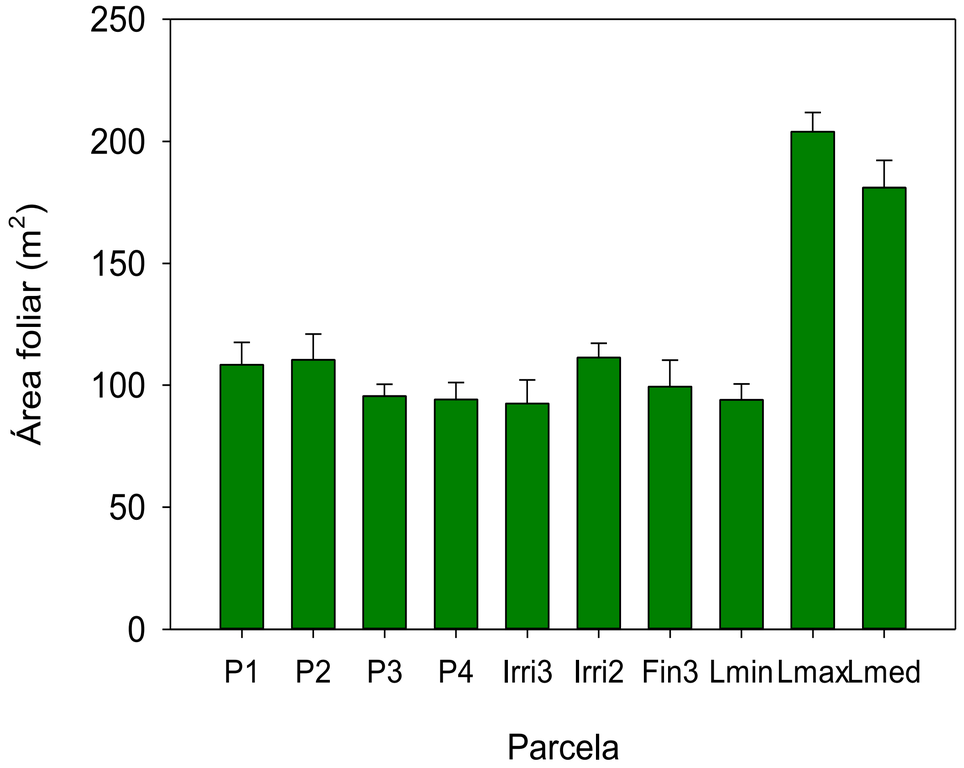
RESULTS

APLICACIÓN FINCA COMERCIAL

LEAF AREA ESTIMATION



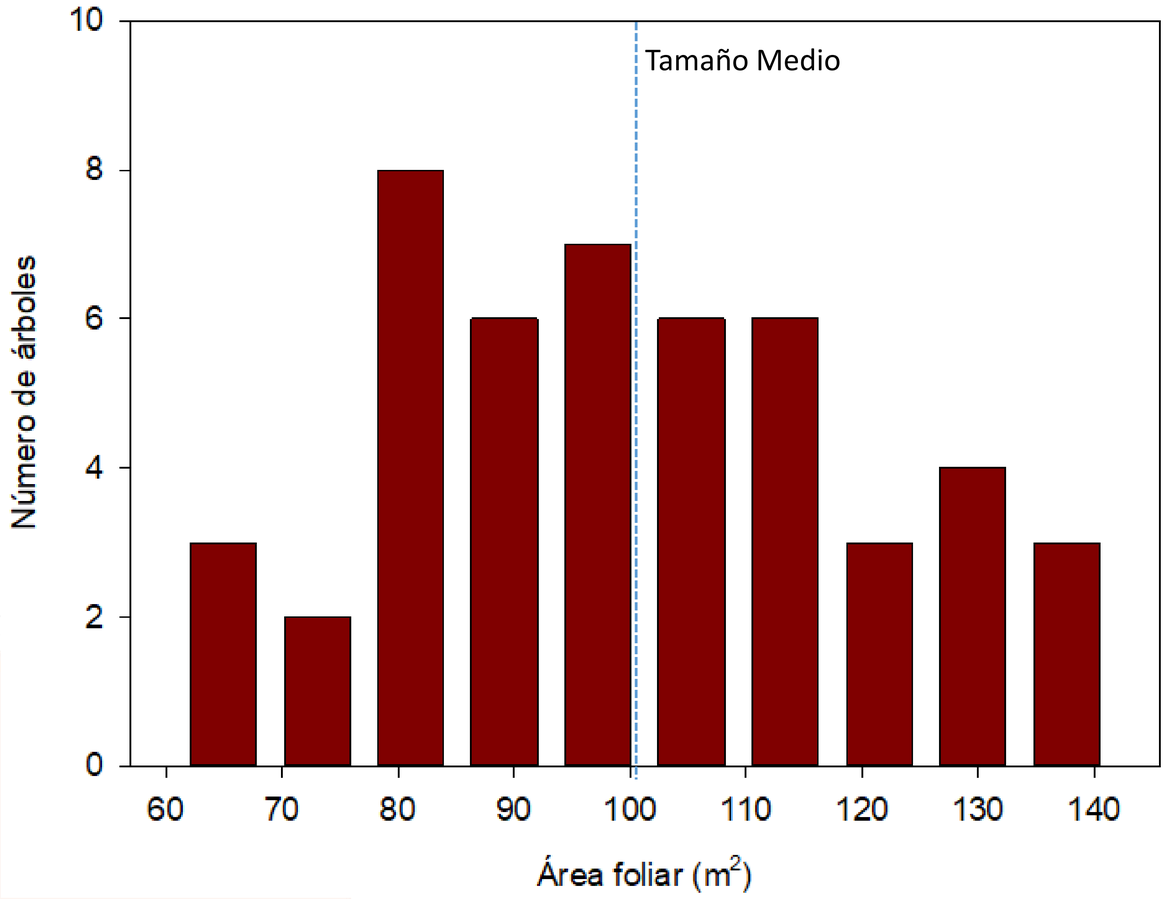




APLICACIÓN FINCA COMERCIAL

RESULTS

TREE SIZE DISTRIBUTION



UNIVERSIDAD PABLO DE OLAVIDE SEVILLA

RESULTS

APLICACIÓN FINCA COMERCIAL

ESTIMATION FROM SENTINEL-2

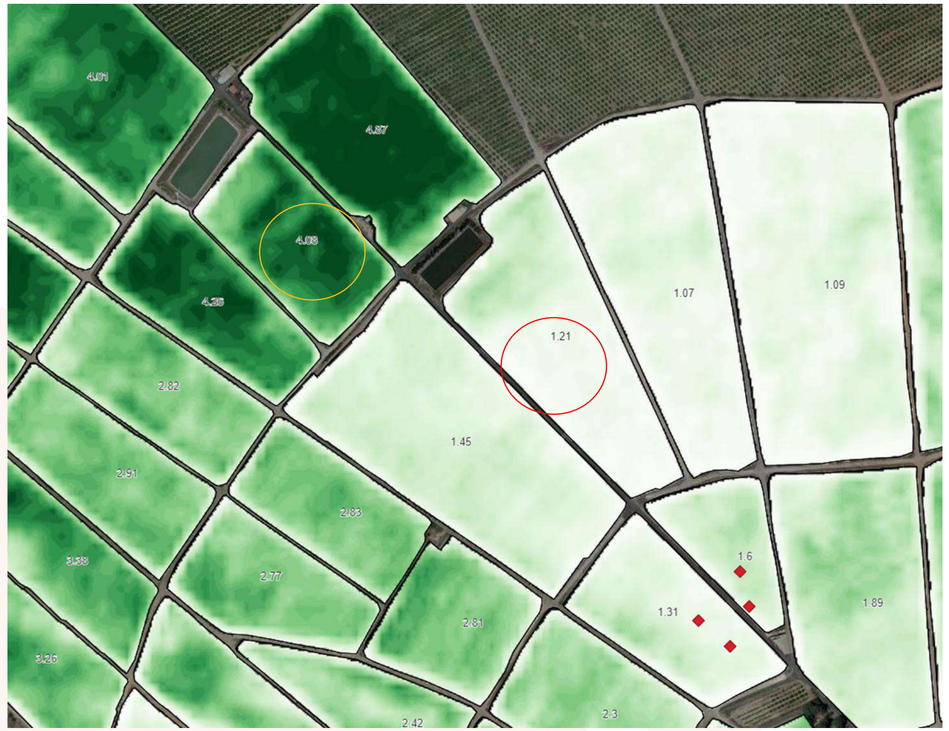
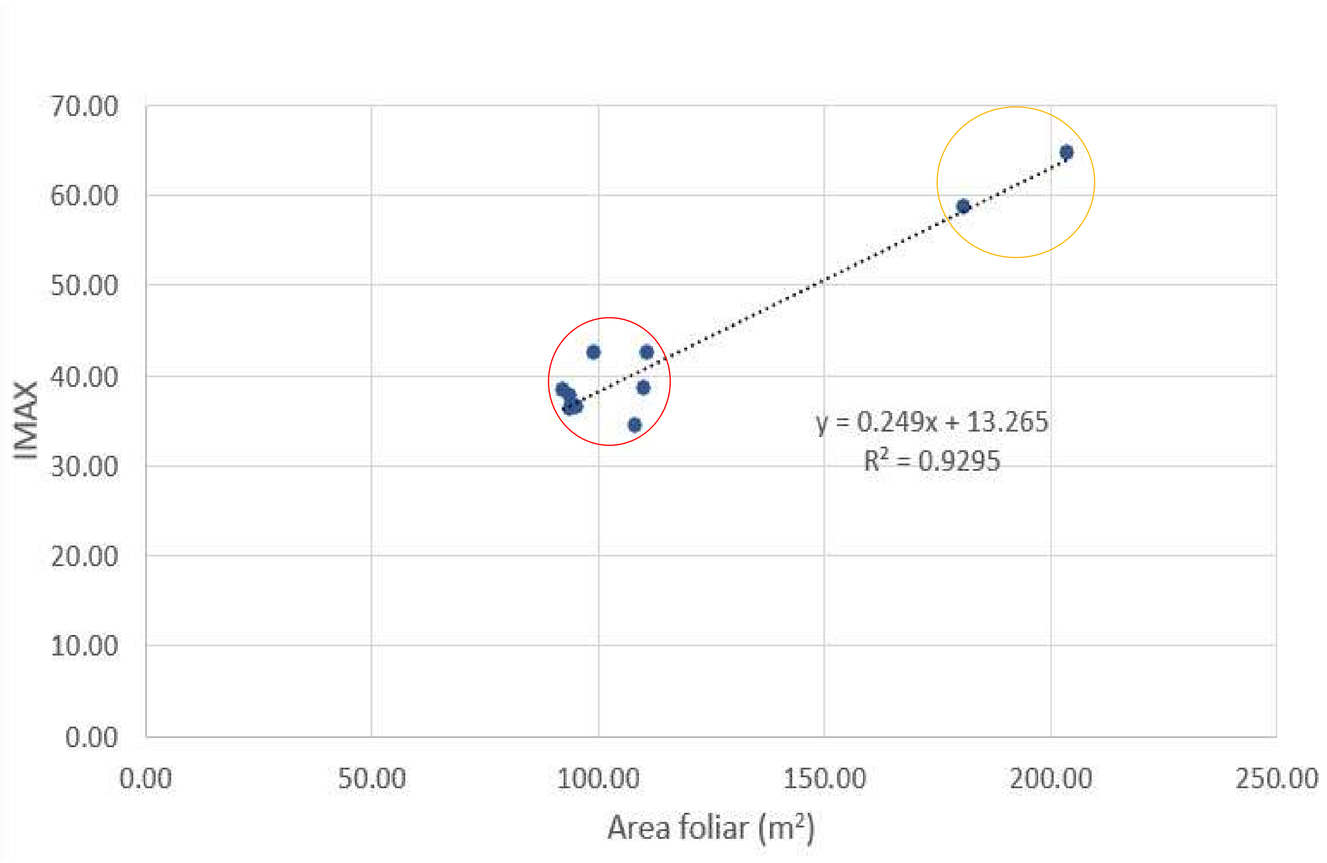


Foto obtenida por Sentinel-2

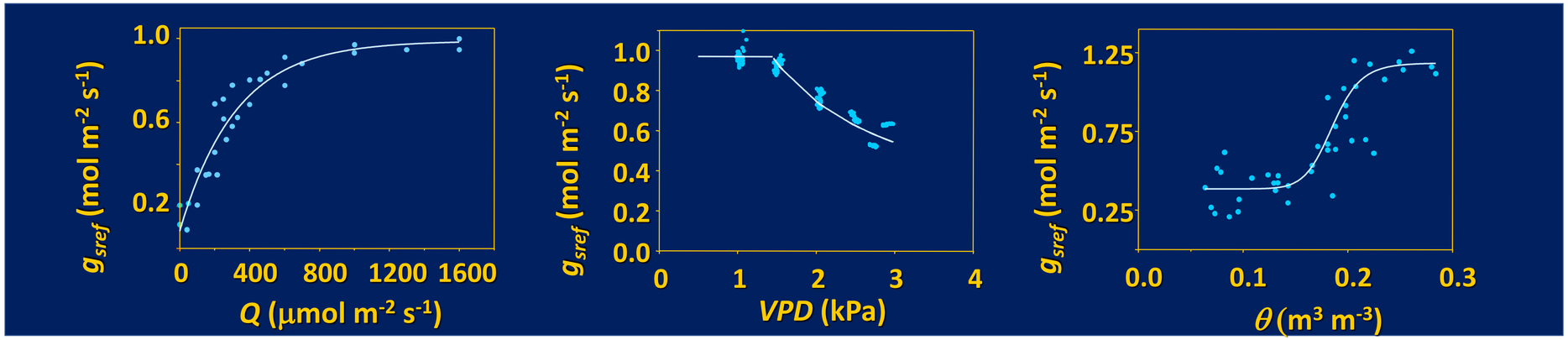


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A model for stomatal conductance

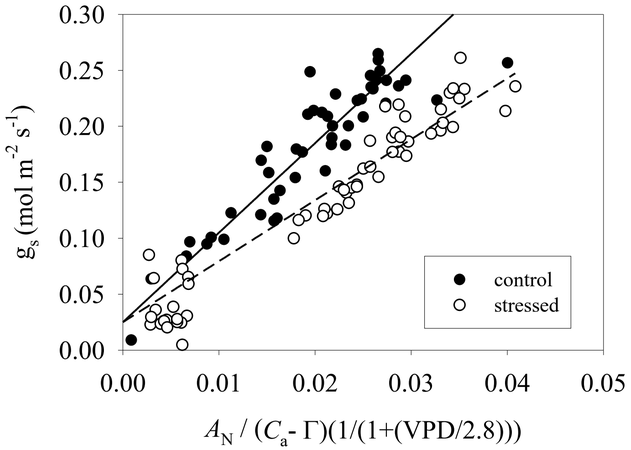
How were g_s models approached before?

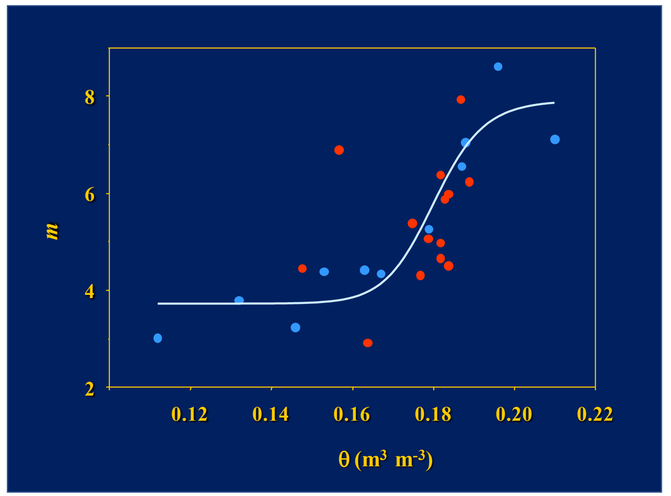
- Jarvis (1976) $g_s = g_{sref} \times f(Q)\, f(T_h)\, f(\mathrm{VPD})\, f(\theta)$



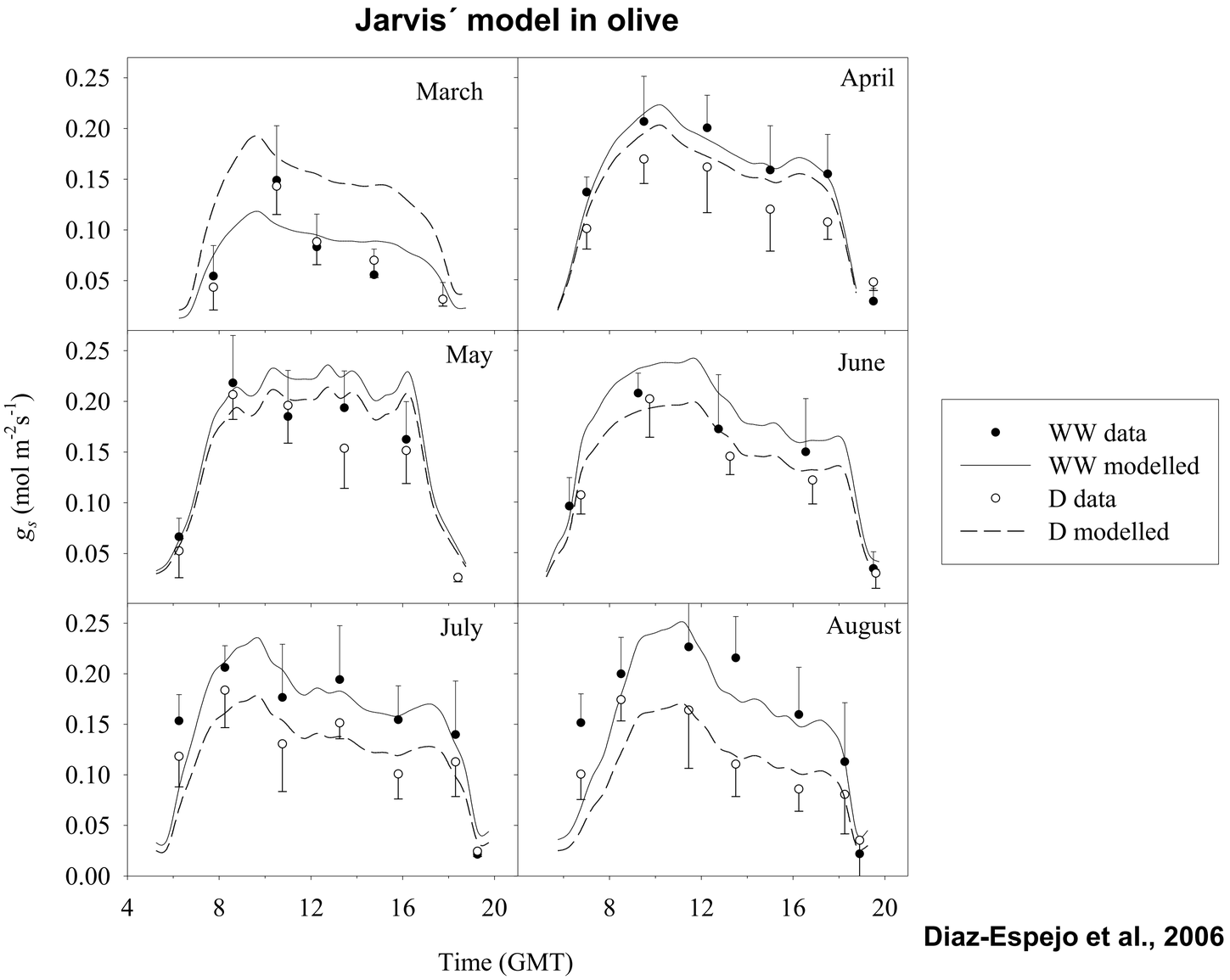
- BWB (1987) or Leuning (1995)

$$g_s = g_0 + m \frac{A\, f(\mathrm{VPD})}{C_a - \Gamma}$$





Models “always” fit



Diaz-Espejo et al., 2006

A mechanistic option: BMF model

- The hydromechanical model by Buckley, Mott and Farquhar (2003)

$$g_s = \frac{\chi(\beta\tau - M)(\Psi_s + \pi_e) - \pi_e + \pi_a}{1 + \chi(\beta\tau - M + \rho)R\,VPD} \quad \xrightarrow{\text{Simplifying}} \quad g_s = \frac{\chi\beta\tau(\Psi_s + \pi_e)}{1 + \chi\beta\tau\,R\,VPD}$$

- Two main assumptions in the simplification:
  1) Mechanical advantage of epidermal cells equals 0.
  2) No significant differences in osmotic pressure between guard and epidermal cells.

Input variables

Soil water potential ($\approx\Psi_{pd}$)
VPD
PPFD
[CO_2]
Temperature
*Osmotic pressure

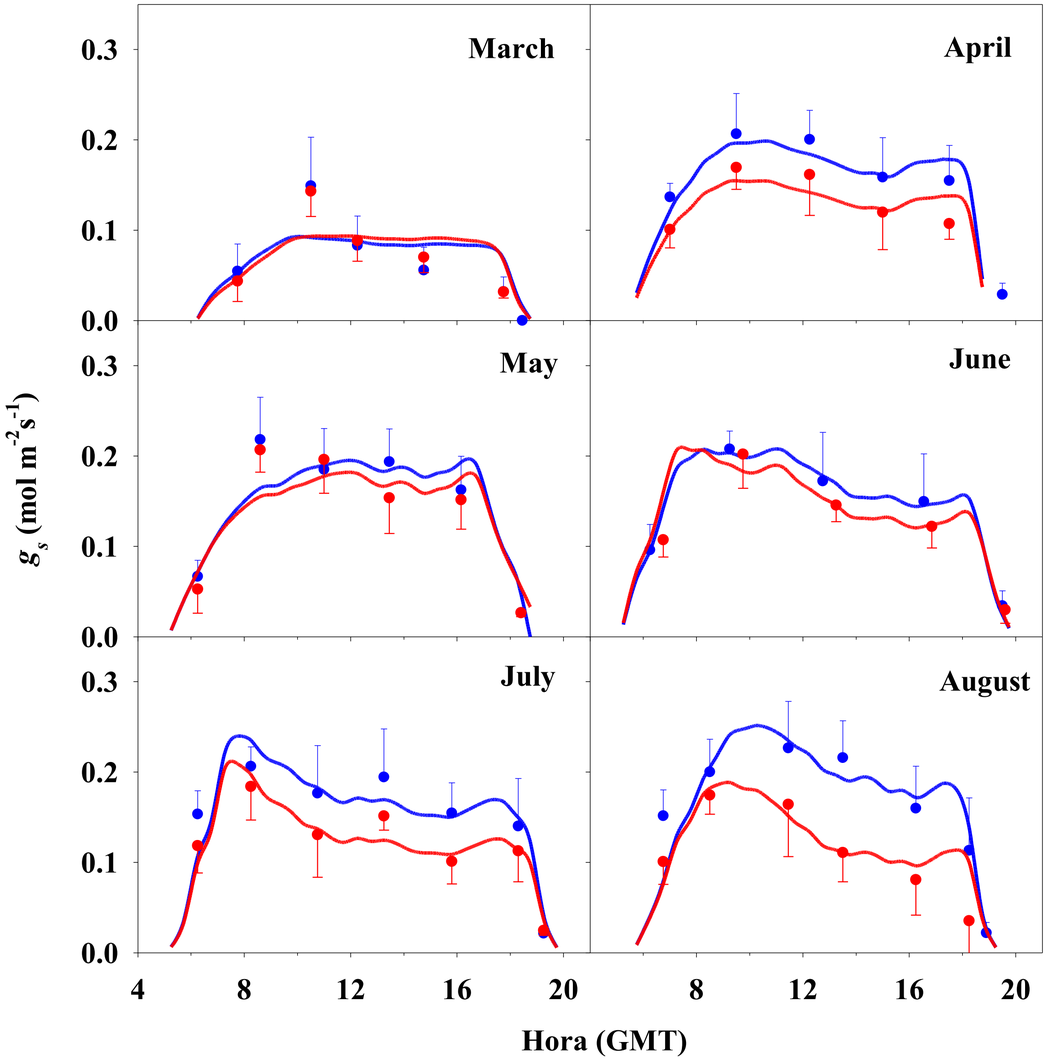
$$g_s = \frac{\chi\beta\tau(\Psi_s + \pi_e)}{1 + \chi\beta\tau\,R\,VPD}$$

Parameters

Plant hydraulic resistance
Guard cells sensitivity to turgor
*Osmotic pressure

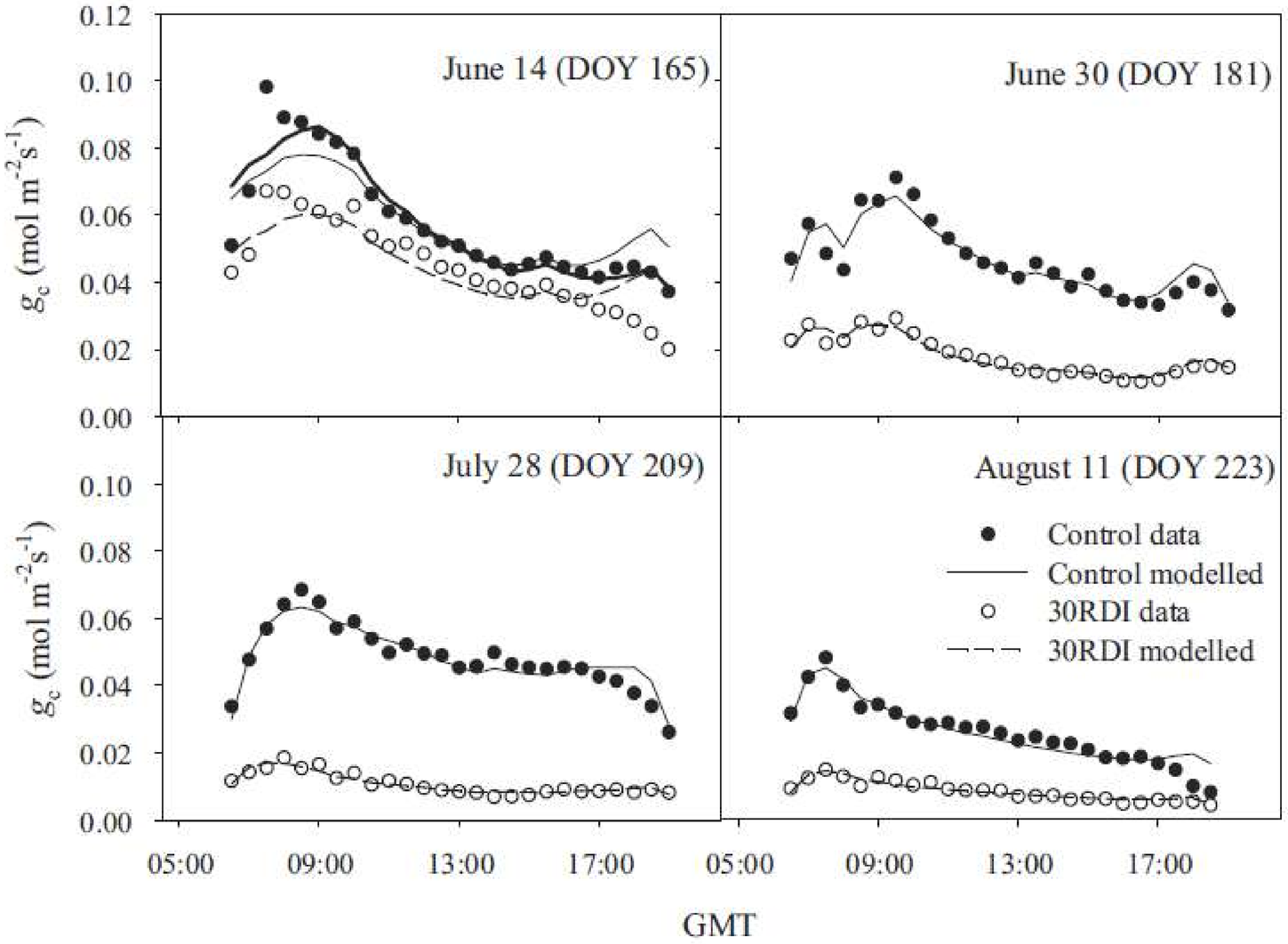
BMF model and olive

Leaf gas exchange

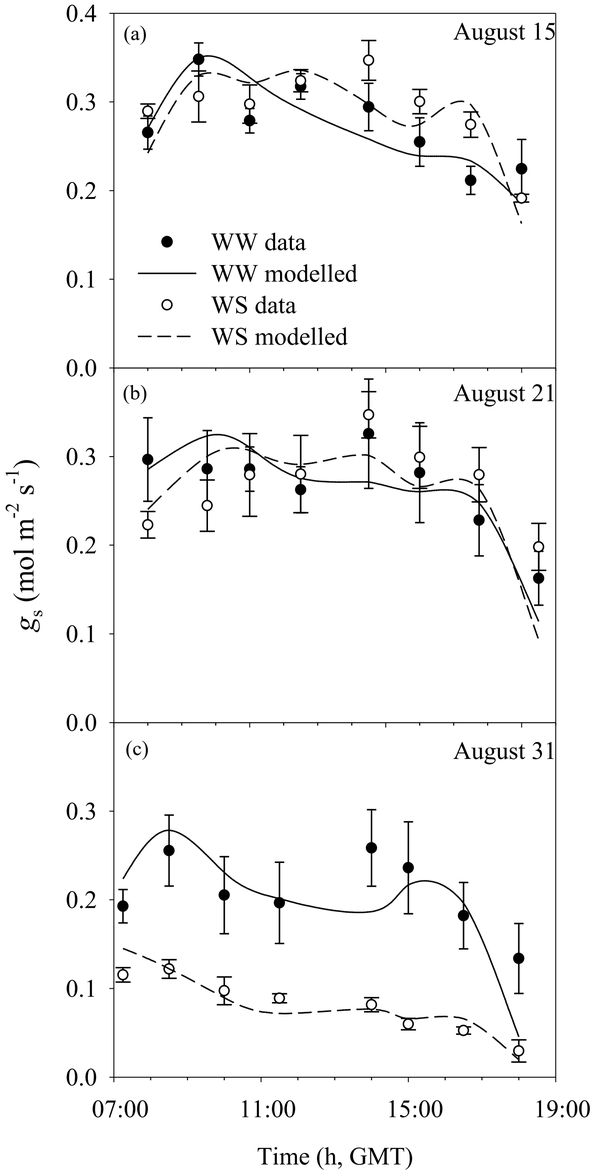


BMF model and olive

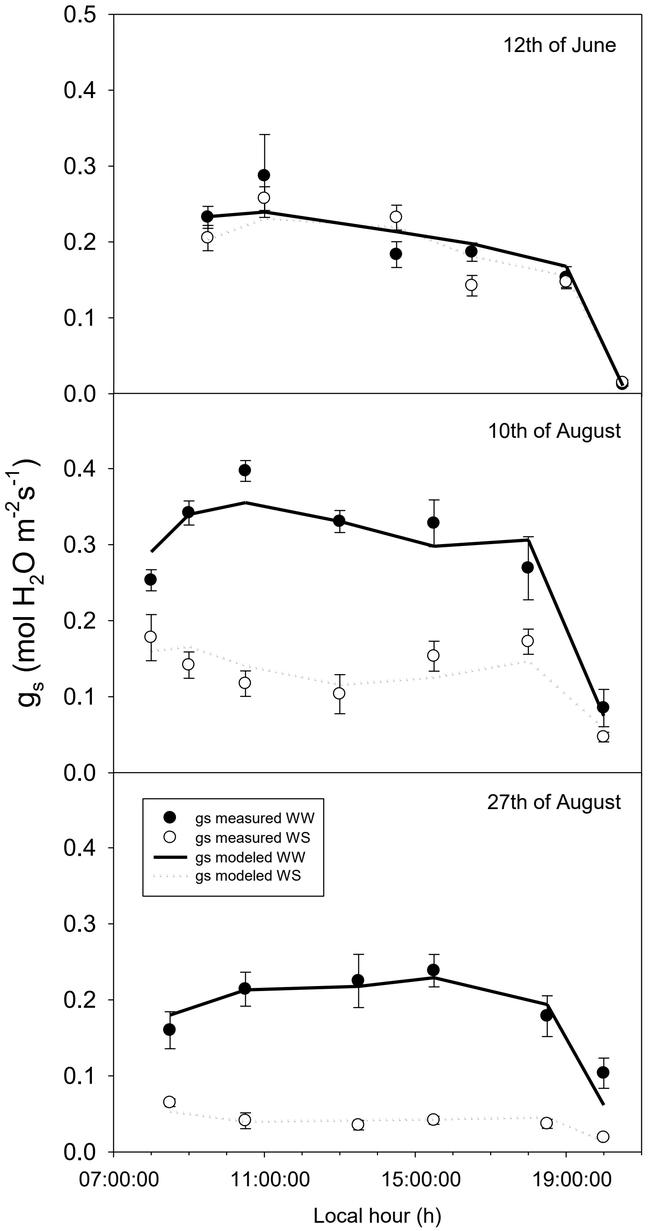
Canopy data



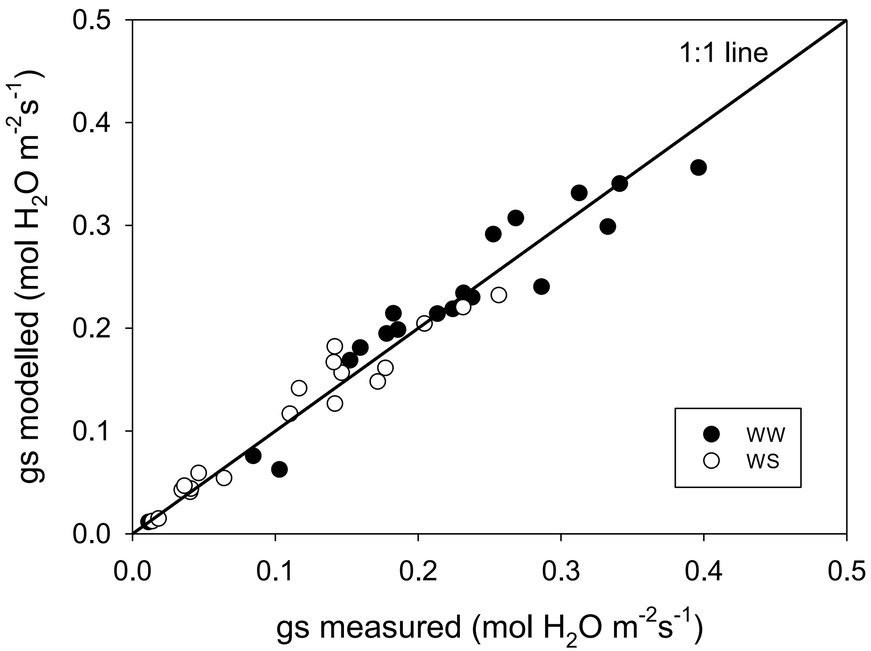
BMF model and almond

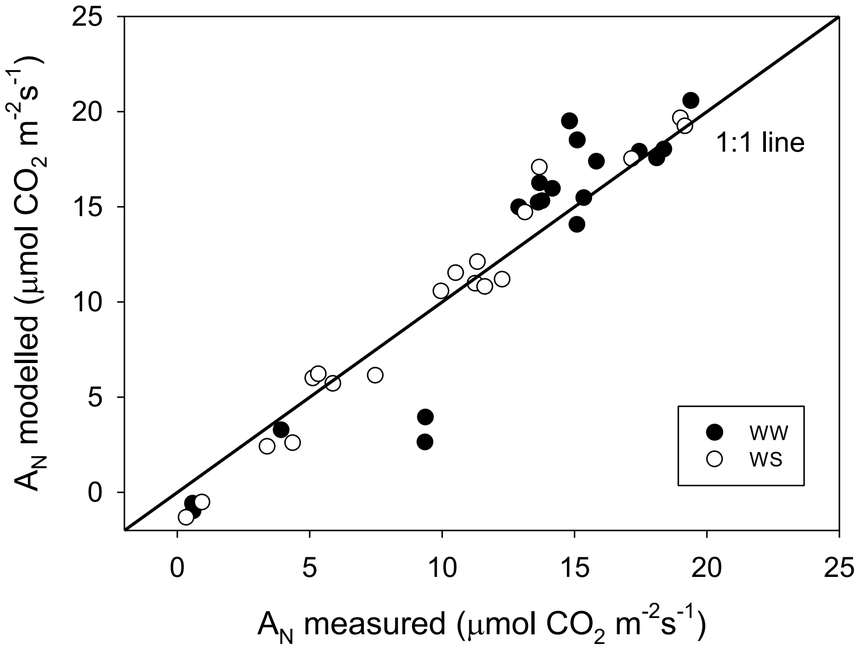


BMF model and grapevine



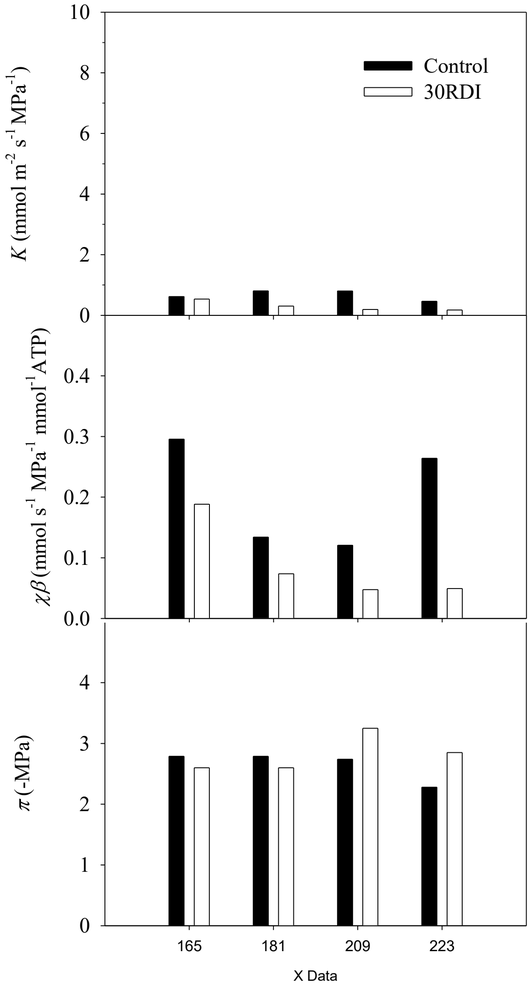
BMF model and grapevine



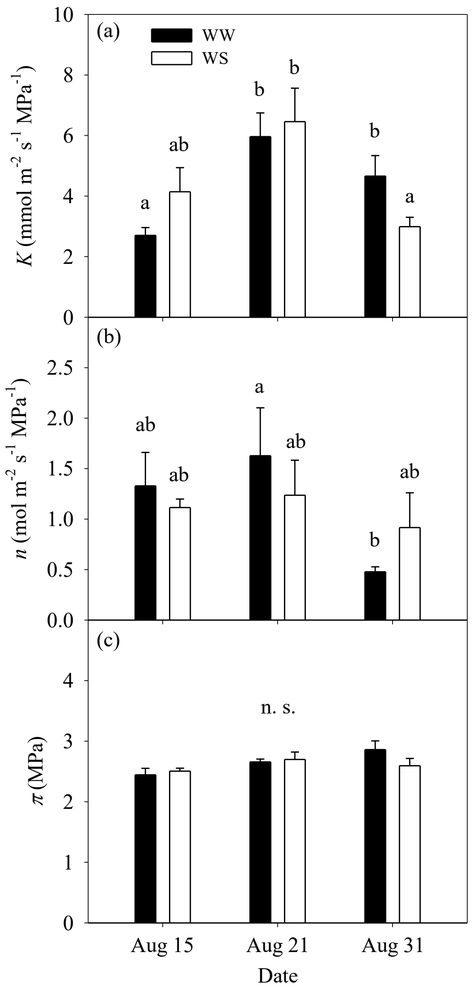


BMF model parameters

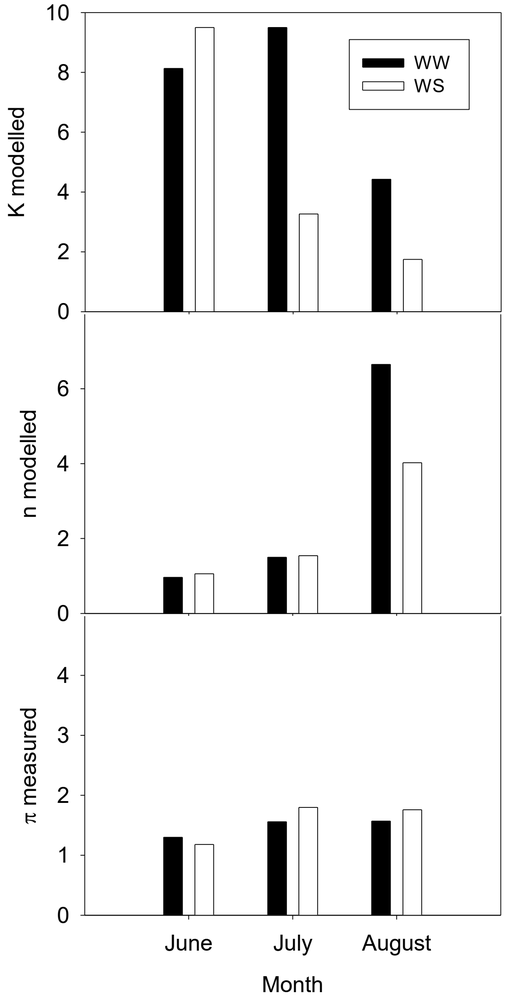
Olive



Almond

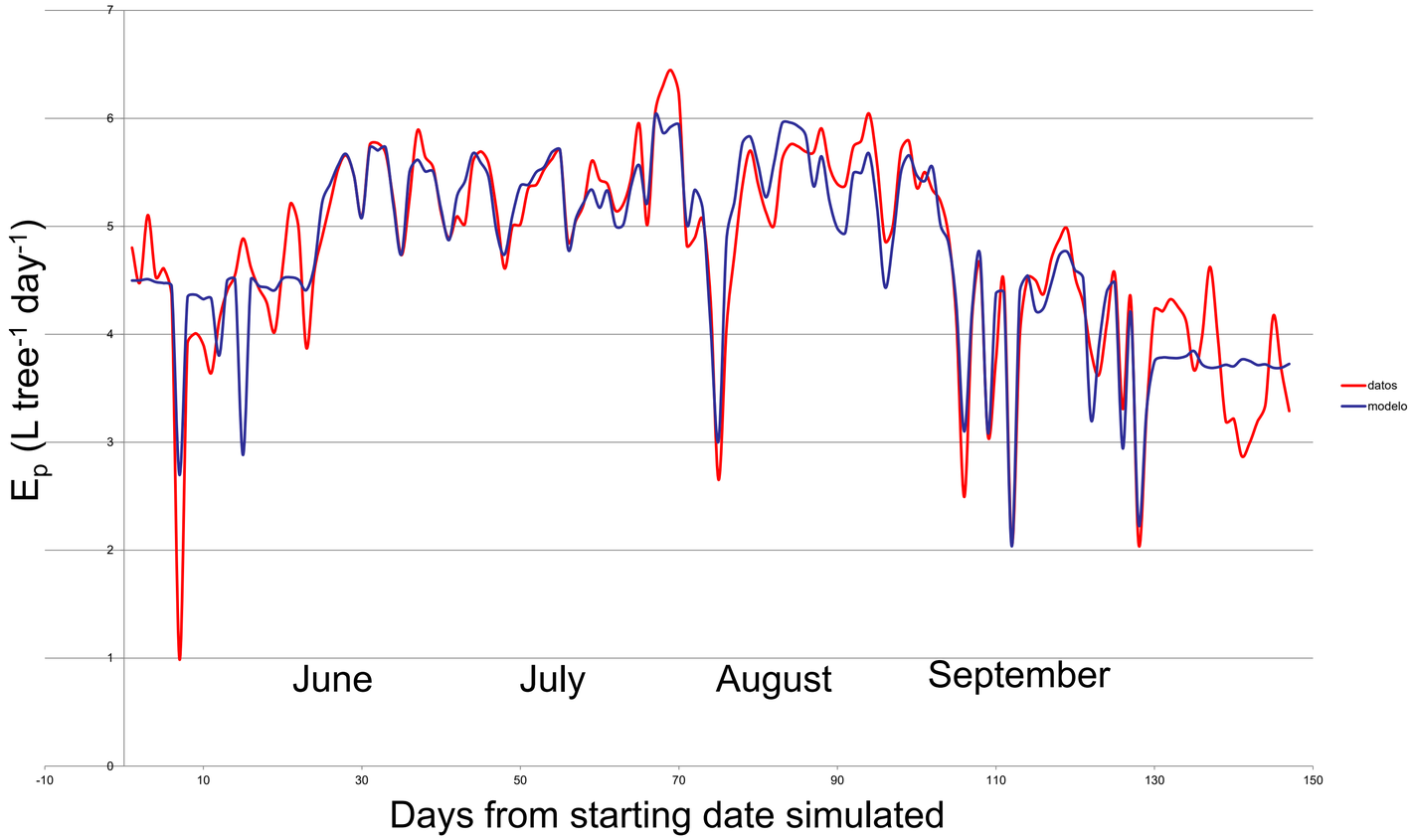


Grapevine



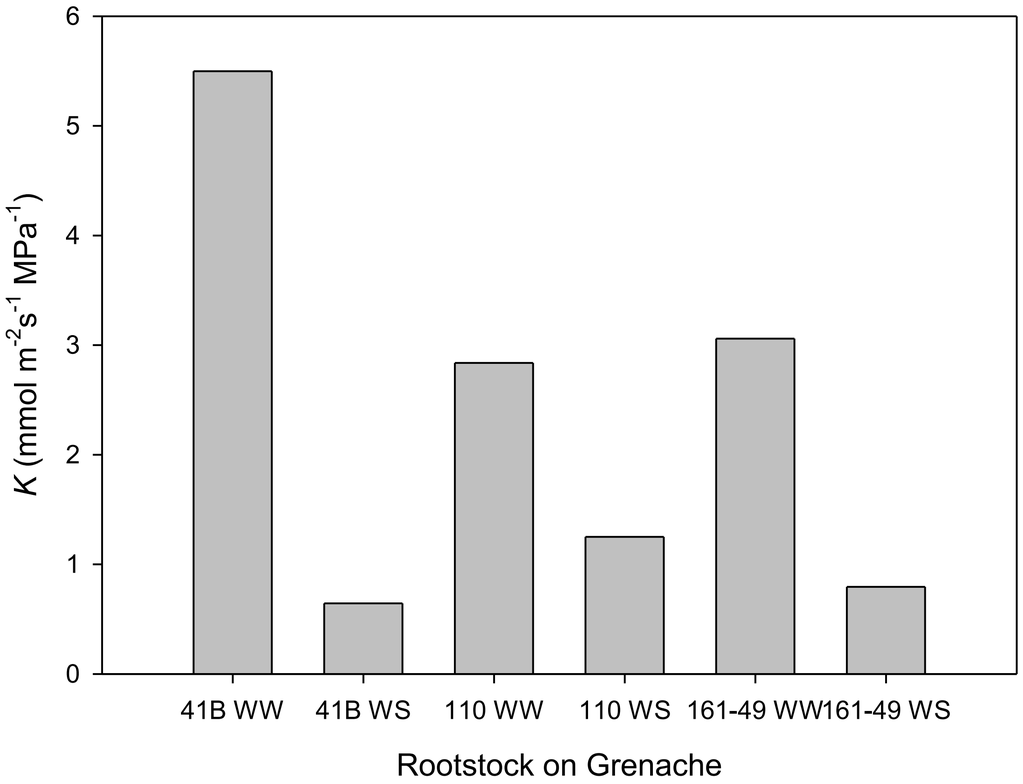
Can we simplify the model further?

Input variables
Daily average VPD
Daily average PPFD
Soil water potential
Leaf area

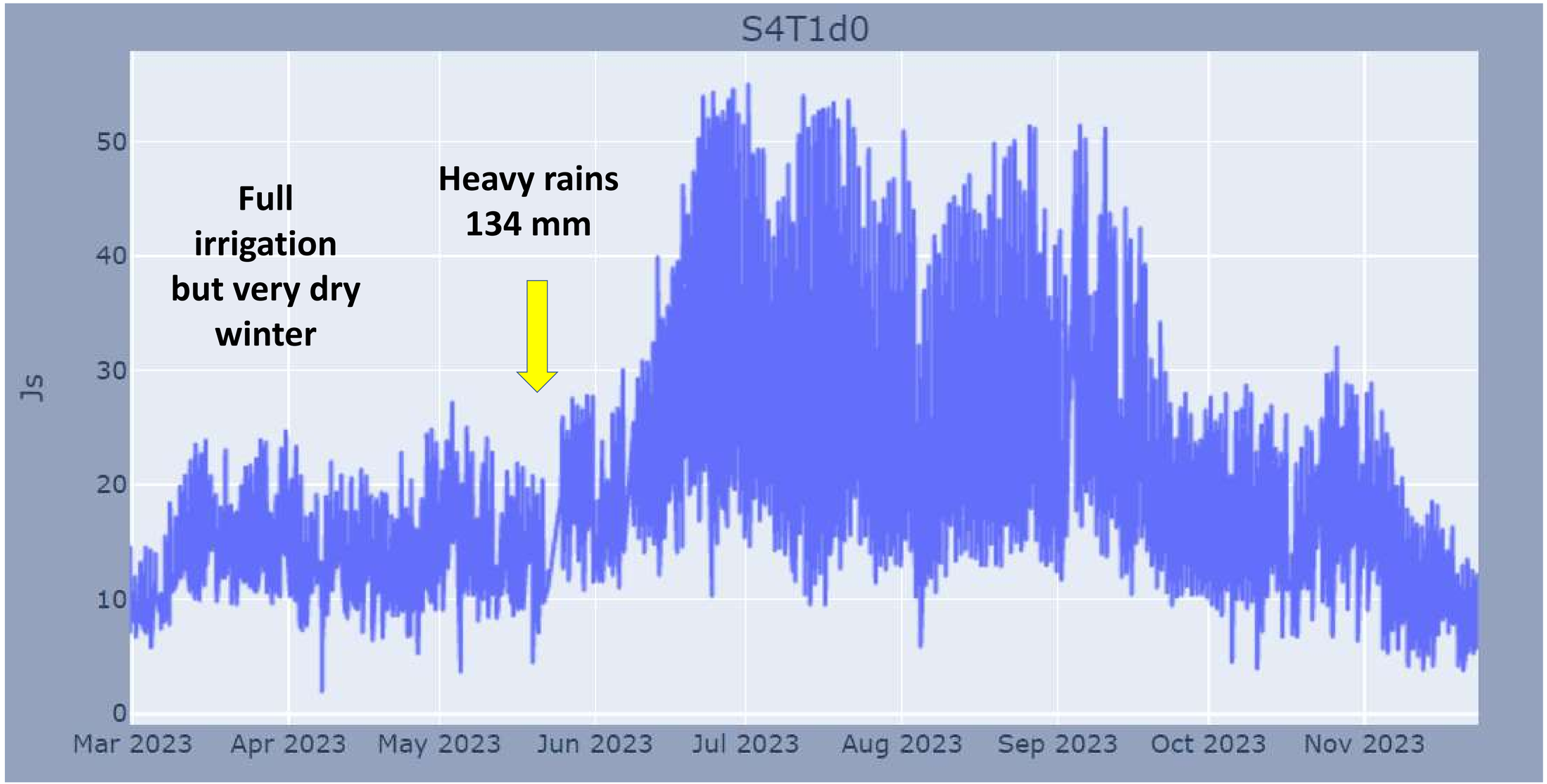


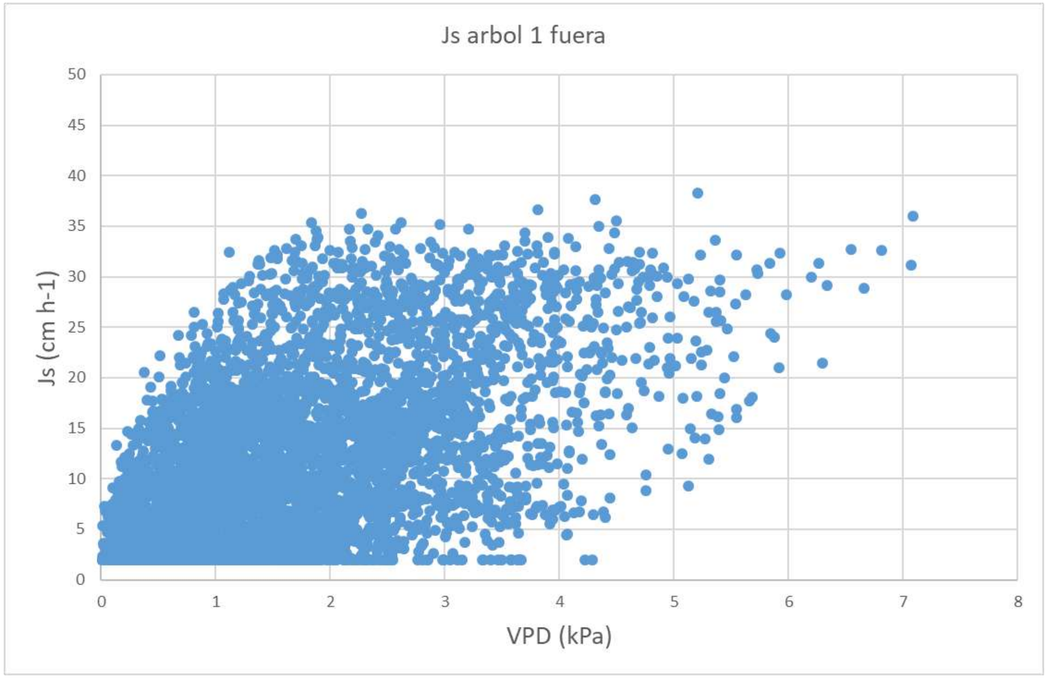
BMF model as a physiological tool to understand rootstocks effect

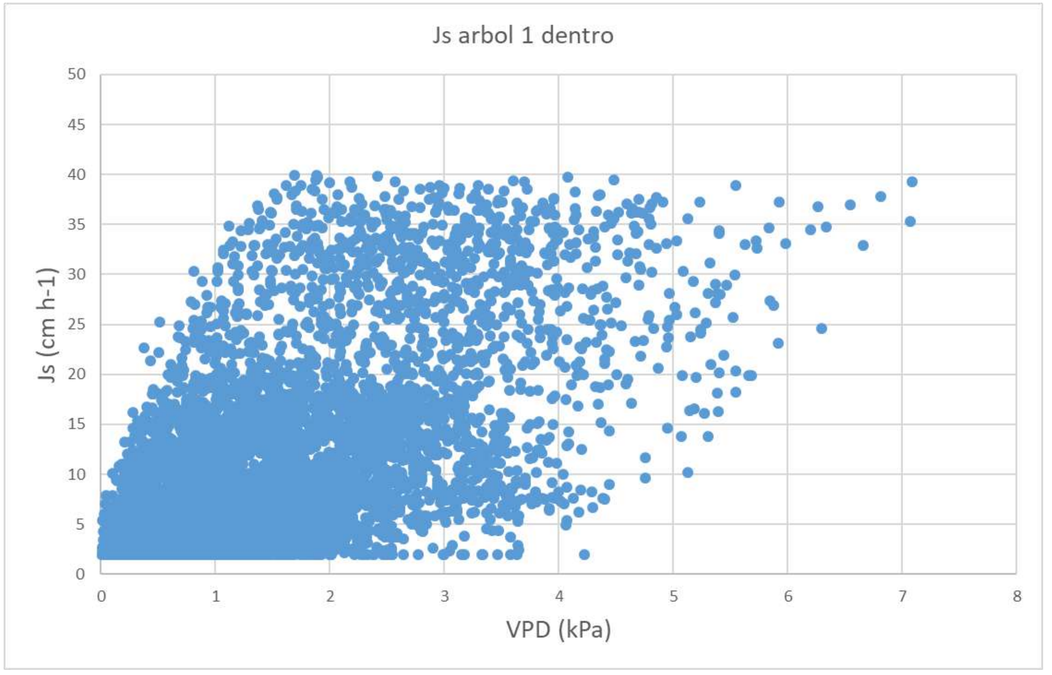
41-B: very vigorous, and medium drought resistant
110-Richter: medium vigorous, drought resistant
161-49: vigorous, drought resistant

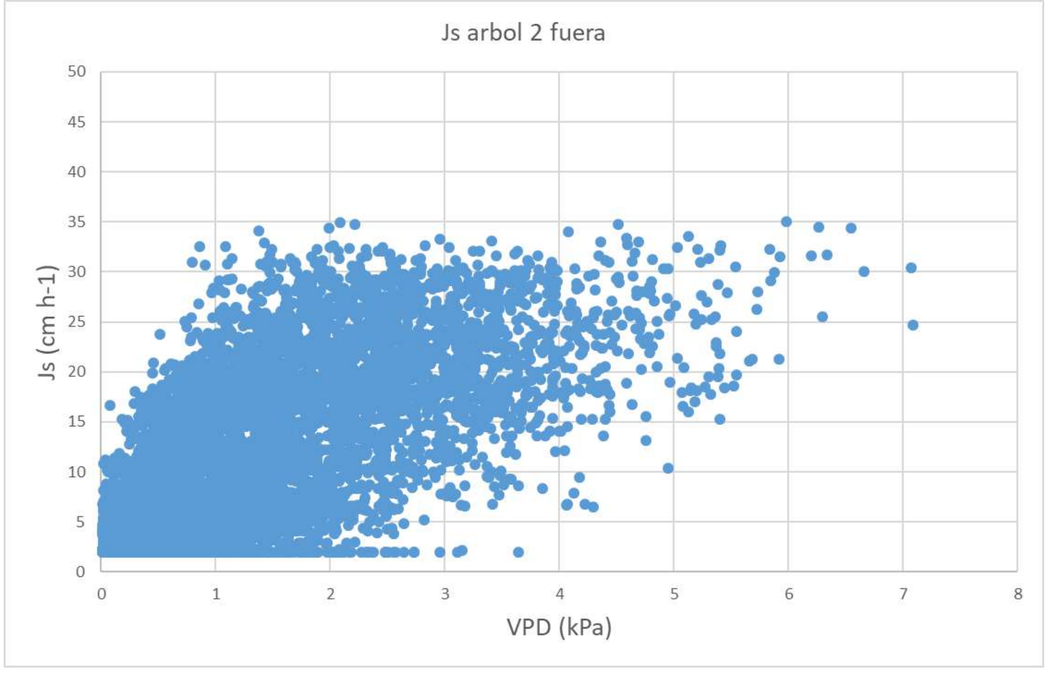


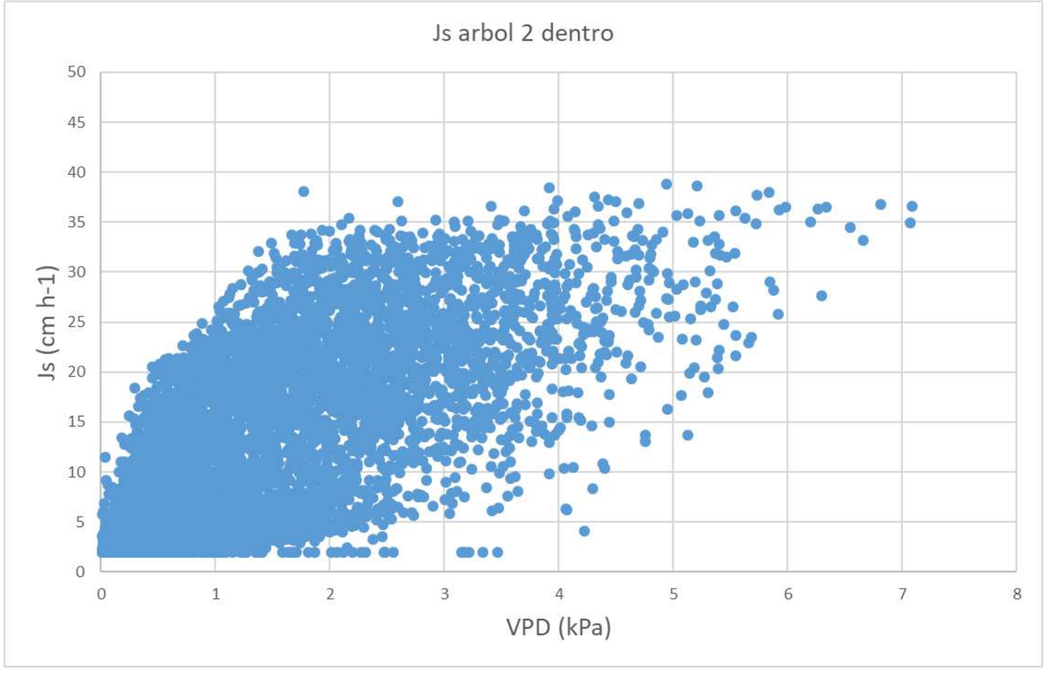
Analysis of sap flow as an advanced diagnosis tool




Js arbol 1 fuera
Js (cm h-1)
VPD (kPa)
0
5
10
15
20
25
30
35
40
45
50
0
1
2
3
4
5
6
7
8


Js arbol 1 dentro
Js (cm h-1)
VPD (kPa)
0
5
10
15
20
25
30
35
40
45
50
0
1
2
3
4
5
6
7
8


Js arbol 2 fuera
Js (cm h-1)
VPD (kPa)
0
5
10
15
20
25
30
35
40
45
50
0
1
2
3
4
5
6
7
8


Js arbol 2 dentro
Js (cm h-1)
VPD (kPa)
0
5
10
15
20
25
30
35
40
45
50
0
1
2
3
4
5
6
7
8

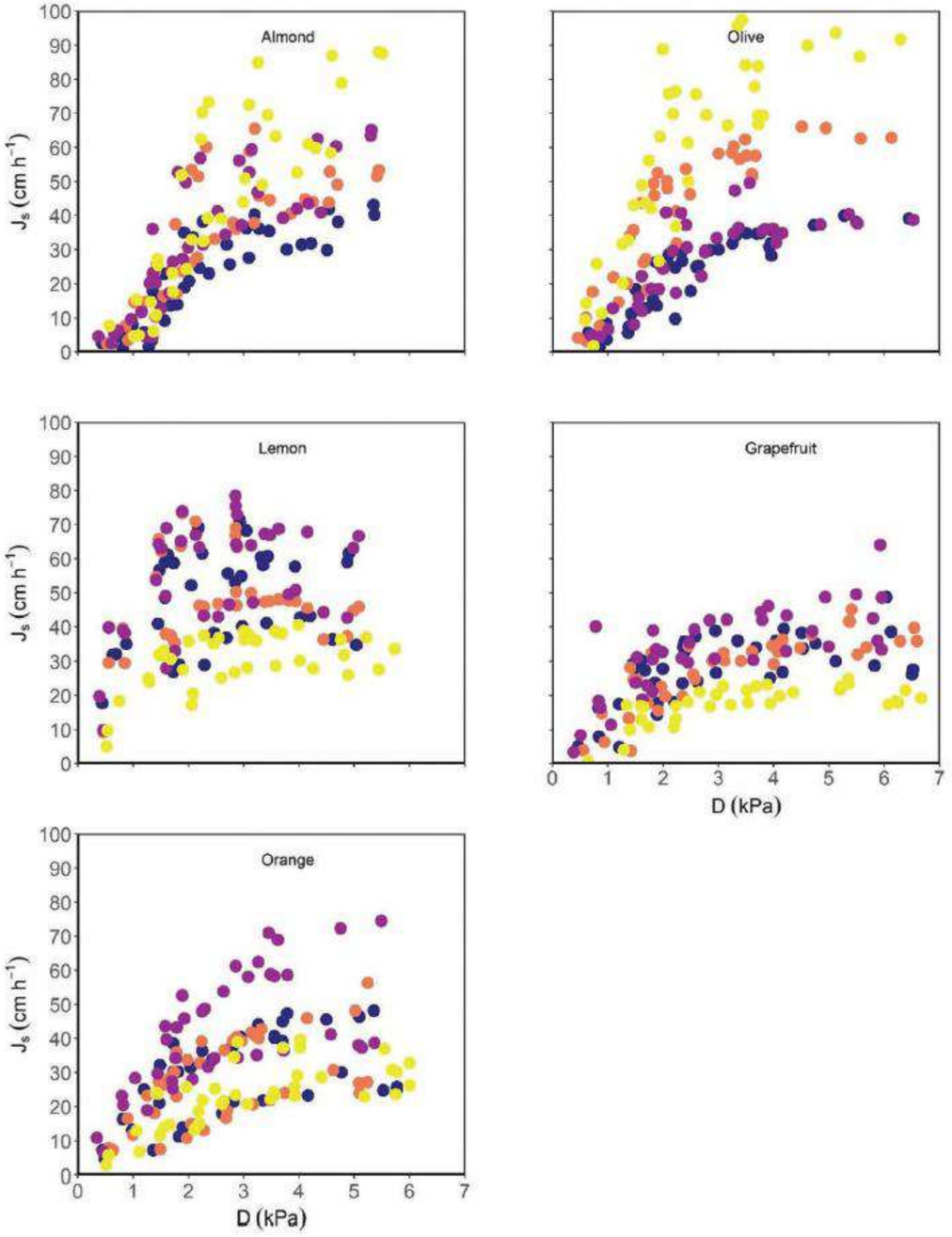
SOCIETY FOR EXPERIMENTAL BIOLOGY

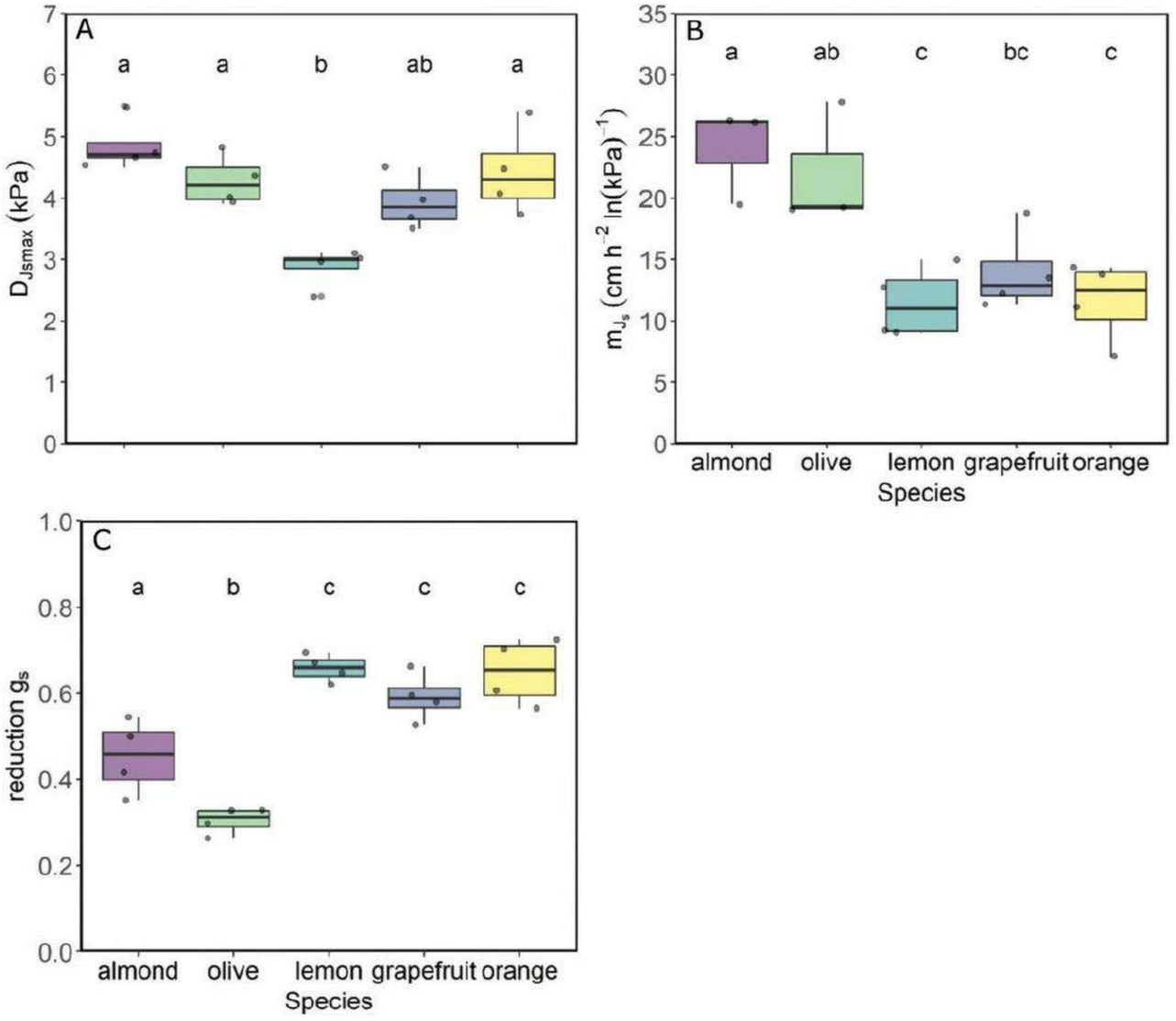
Journal of Experimental Botany
https://doi.org/10.1093/jxb/erad157 Advance Access Publication 28 April 2023

RESEARCH PAPER

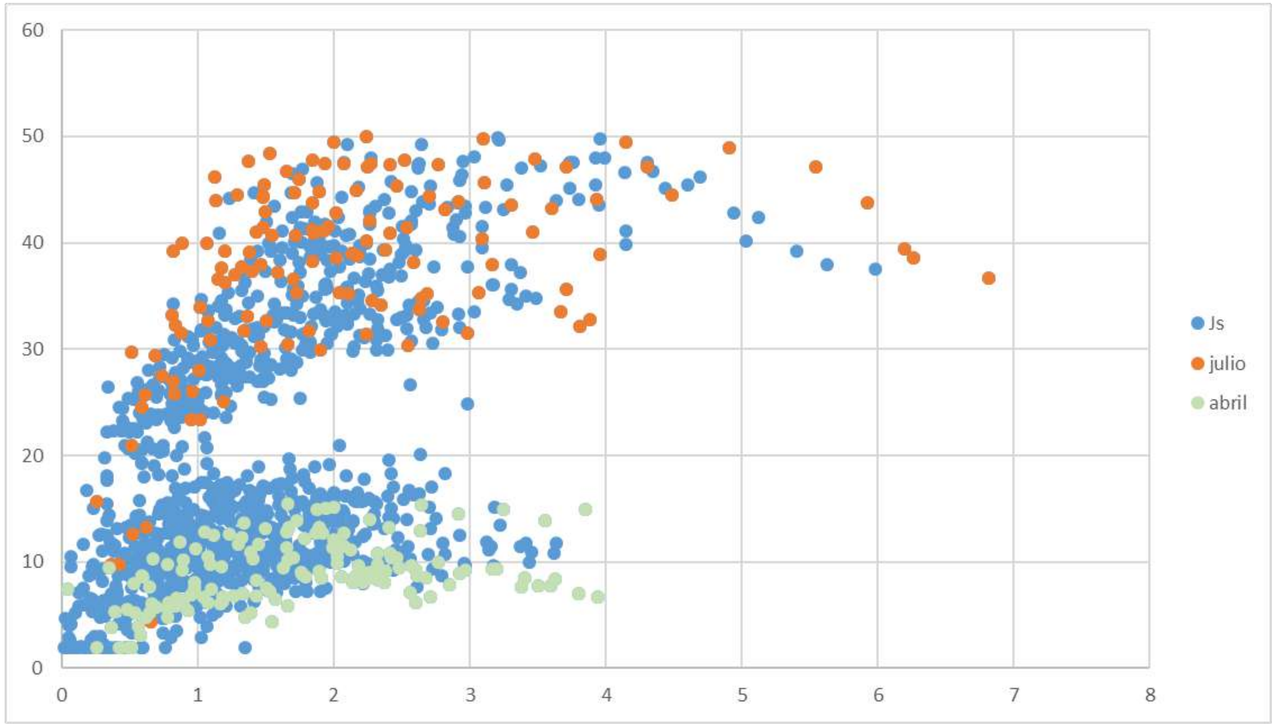
Role of hydraulic traits in stomatal regulation of transpiration under different vapour pressure deficits across five Mediterranean tree crops

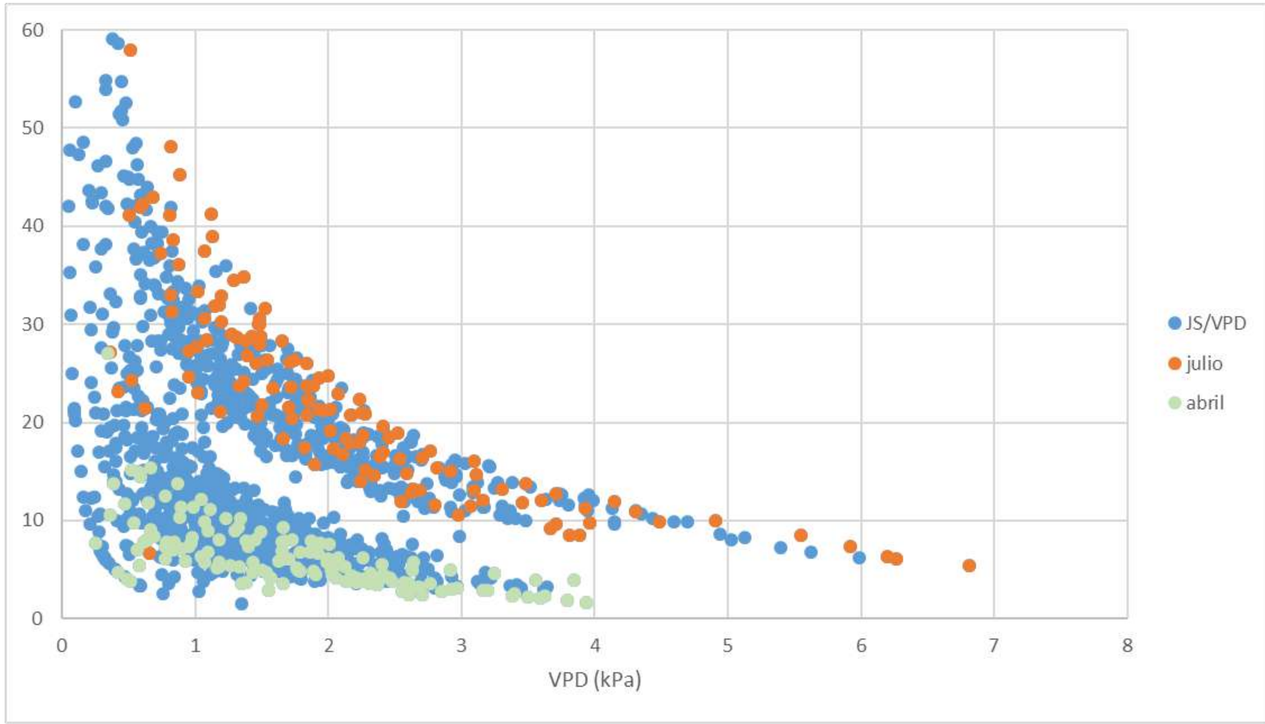
Virginia Hernandez-Santana[1,2,*], Celia M. Rodriguez-Dominguez[1,2], Jaime Sebastian-Azcona[1], Luis Felipe Perez-Romero[3] and Antonio Diaz-Espejo[1,2]


Almond
Olive
Lemon
Grapefruit
Orange
J_s (cm h^{-1})
D (kPa)


A
a a b ab a
D_{Jsmax} (kPa)
B
a ab c bc c
m_{J_s} (cm h^{-2} ln(kPa)$^{-1}$)
almond olive lemon grapefruit orange
Species
C
a b c c c
reduction g_s
almond olive lemon grapefruit orange
Species

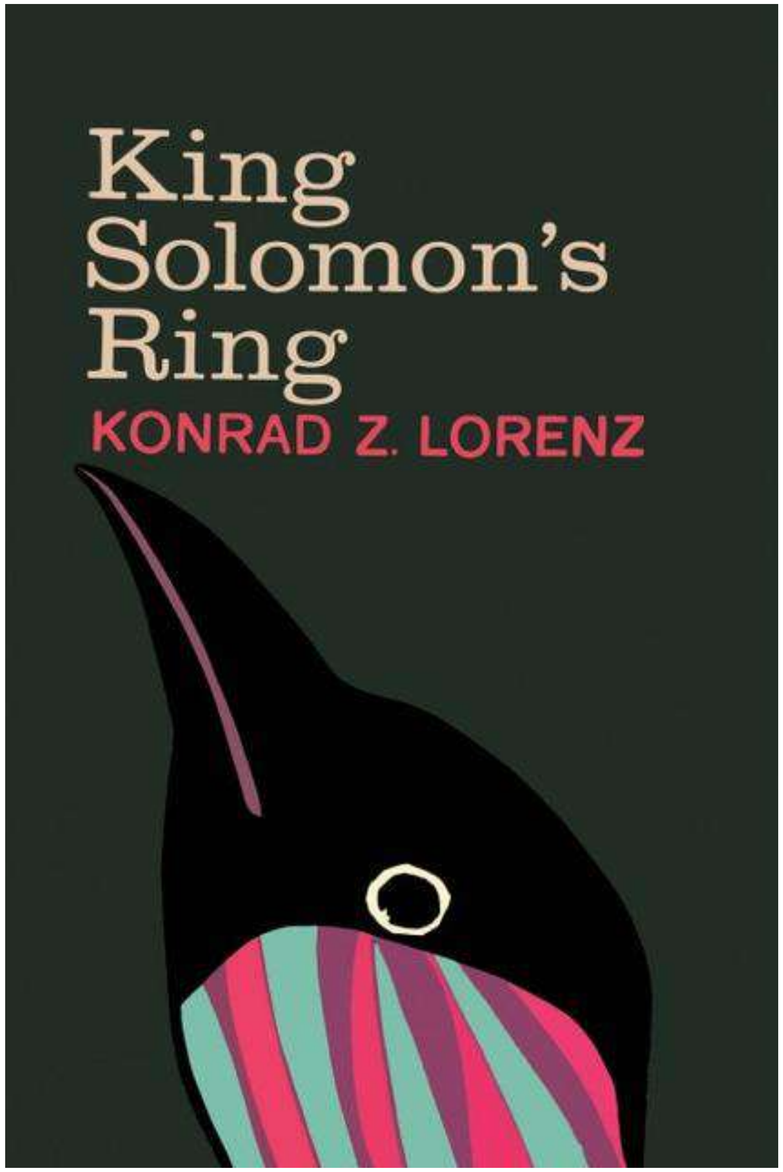
Analysis of sap flow as an advanced diagnosis tool





The increment of sap flux density with VPD maintaining the same maximum VPD can only be explained by hydraulic limitations, in this case, soil hydraulic limitations.

Use of sensors to estimate stomatal conductance


King
Solomon's
Ring
KONRAD Z. LORENZ

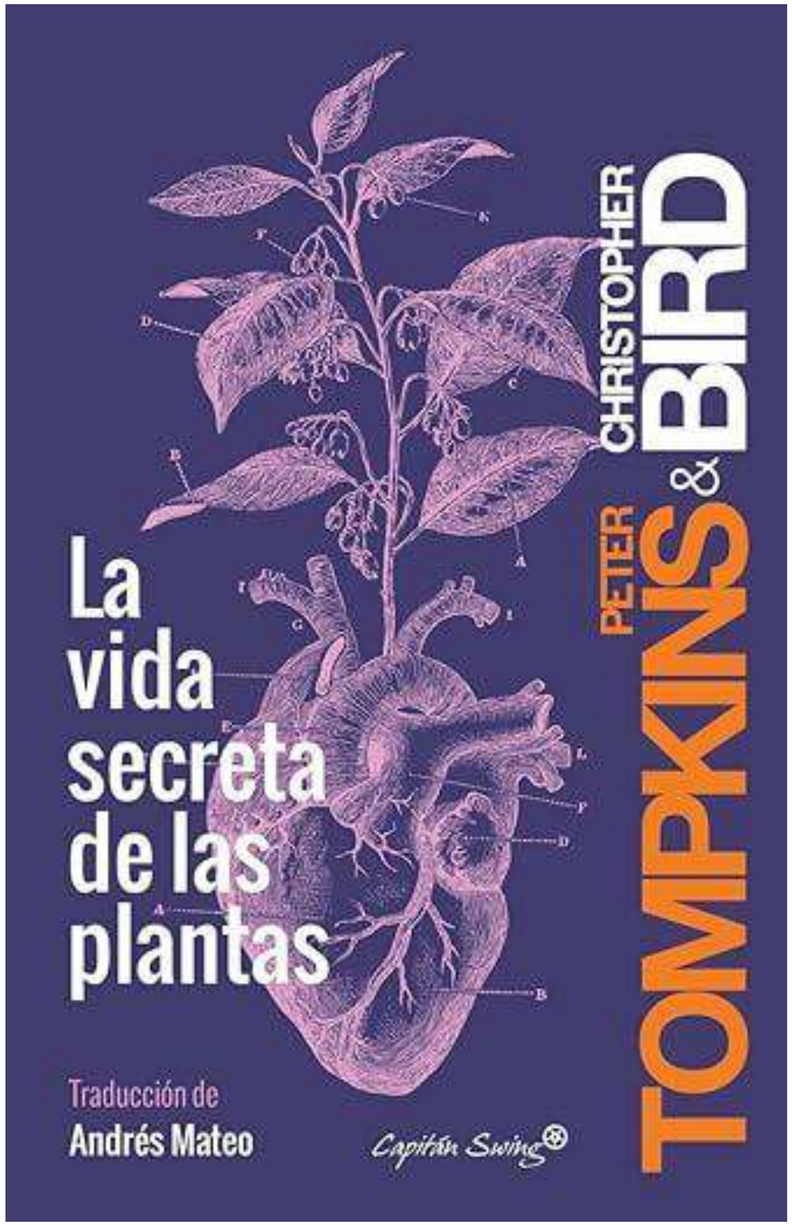


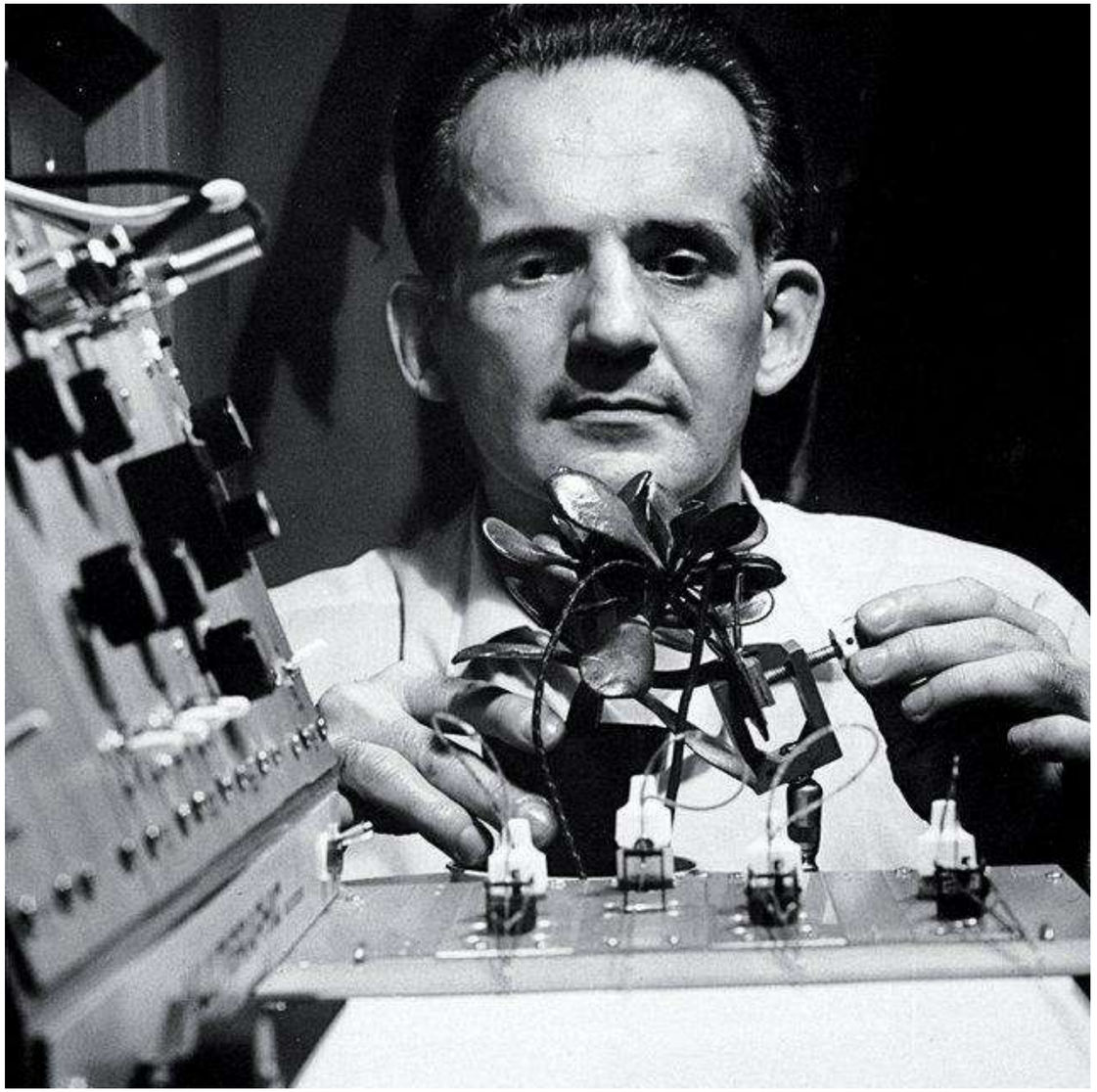

MS

Electric signals communication

Volatiles communication





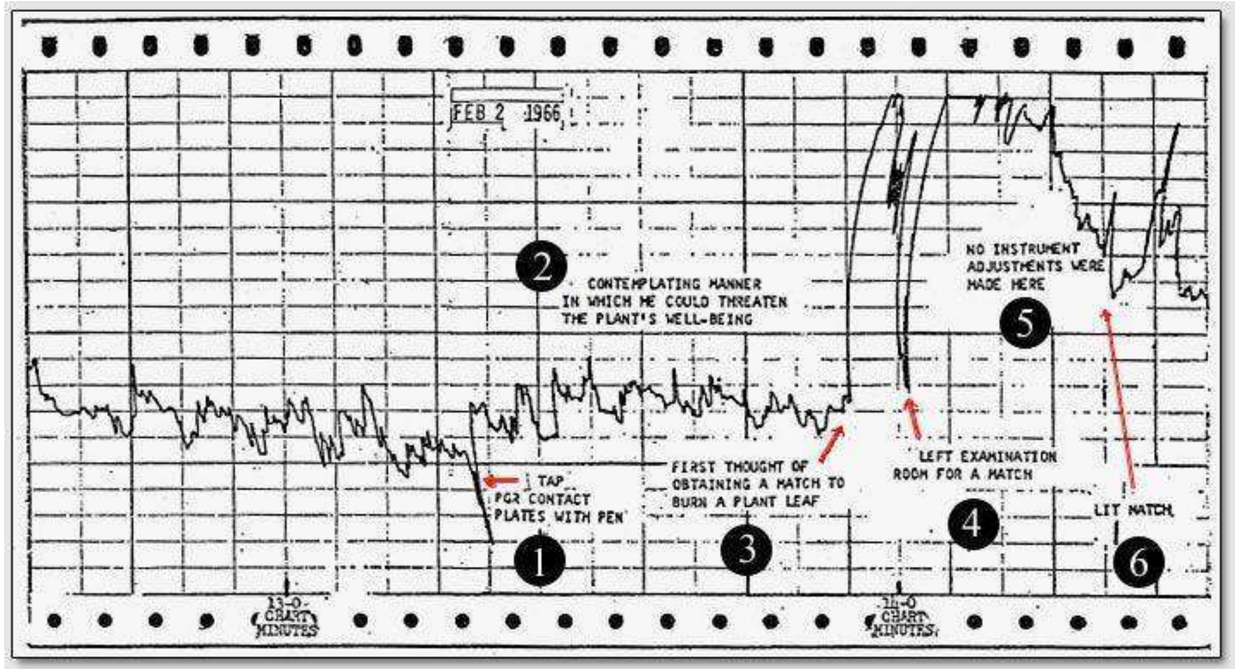


The New York Times Magazine
THE LIVES THEY LIVED

CLEVE BACKSTER

He talked to plants. And they talked back.

Cleve Backster (1924–2013), a CIA interrogation specialist, was famous for unconventionally testing **plants** with his Polygraph machine a.k.a. lie detector.



la cuadratura del círculo

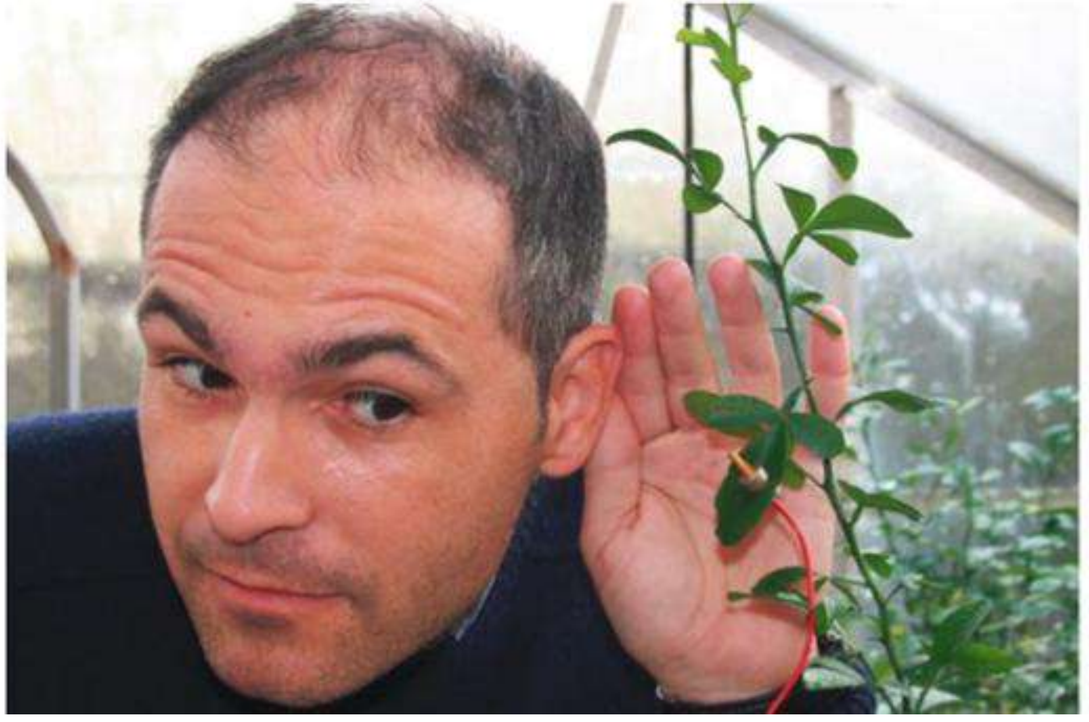
¿Y si las plantas hablaran?

Las plantas notan que les falta agua para continuar su actividad, bien por falta de agua en suelo o por condiciones meteorológicas desfavorables, y generan unas señales que podemos medir de forma automática y continua y monitorizar, ya sea con el PC de nuestra oficina o con nuestro smartphone.

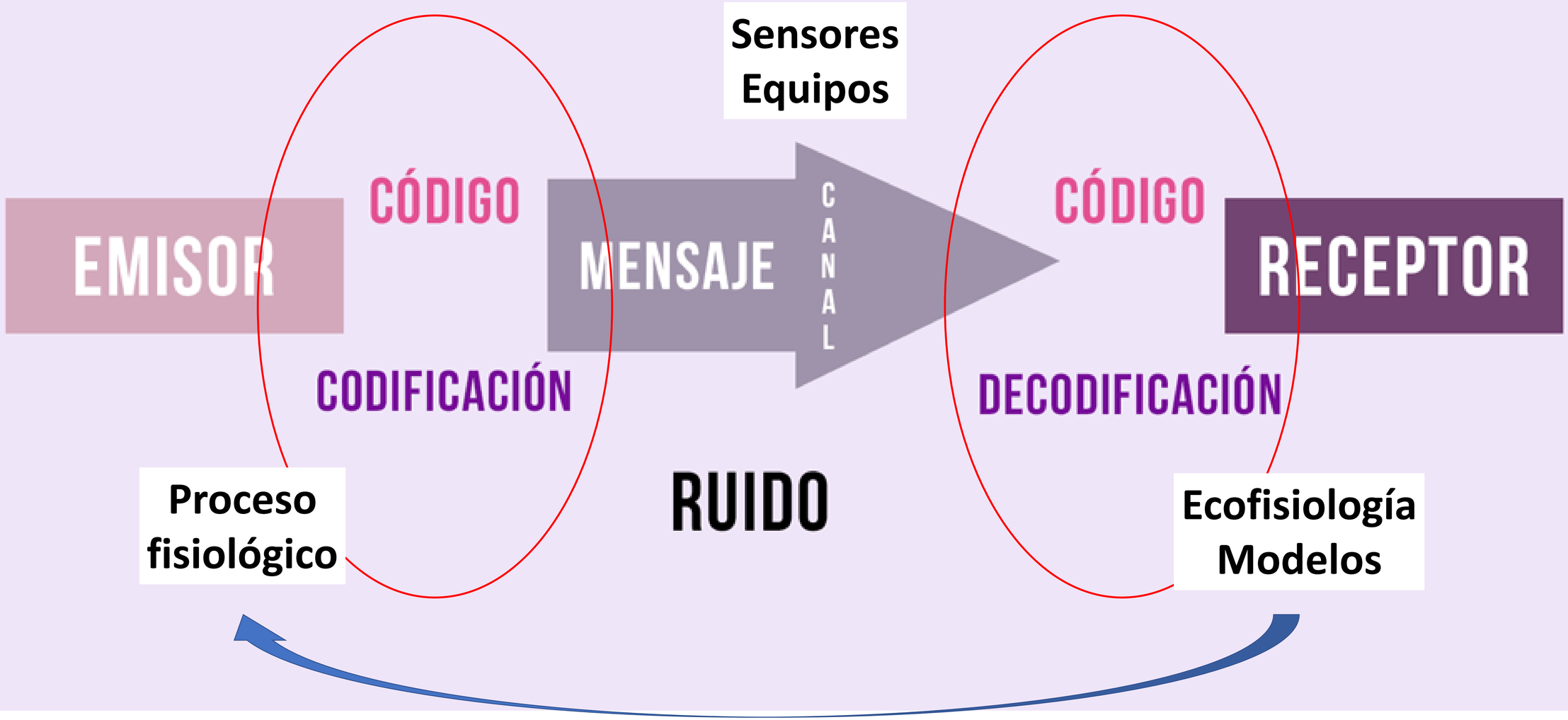
Antonio Díaz Espejo - Instituto de Recursos Naturales y Agrobiología (IRNAS/CSIC)

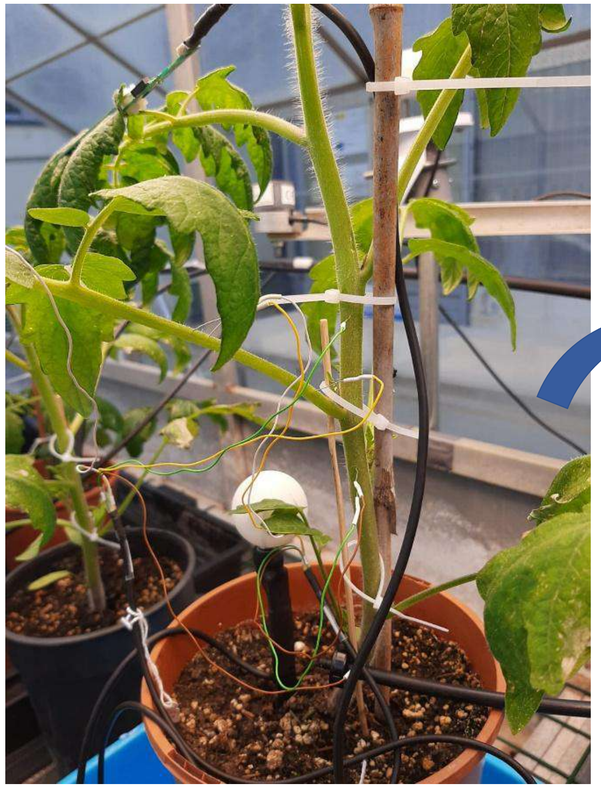
22/01/2015 - 22:57h

Compartir 19 Me gusta Twittear 10



ELEMENTOS DE LA COMUNICACIÓN





la cuadratura del círculo

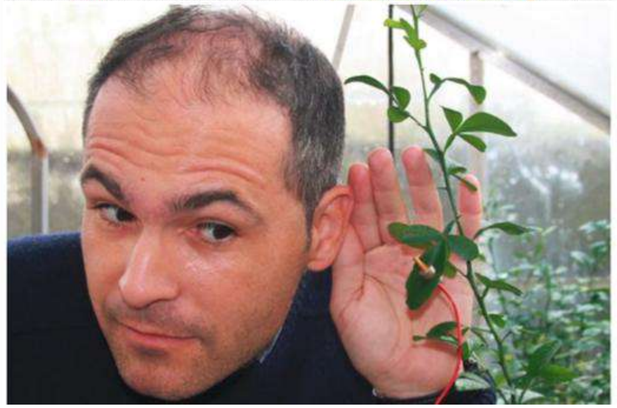
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Las plantas notan que les falta agua para continuar su actividad, bien por falta de agua en suelo o por condiciones meteorológicas desfavorables, y generan unas señales que podemos medir de forma automática y contínua y monitorizar, ya sea con el PC de nuestra oficina o con nuestro smartphone.

Antonio Díaz Espejo - Instituto de Recursos Naturales y Agrobiología (IRNAS/CSIC)

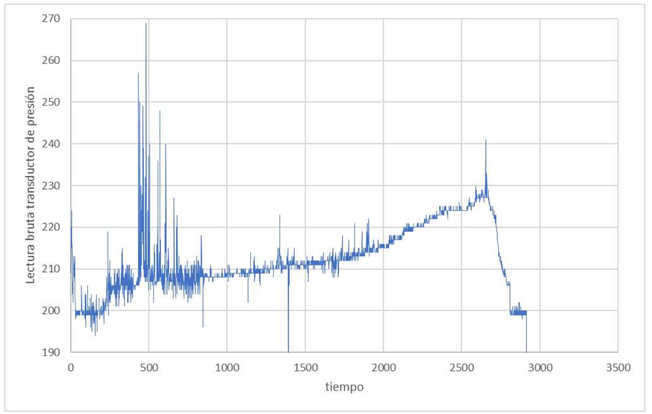
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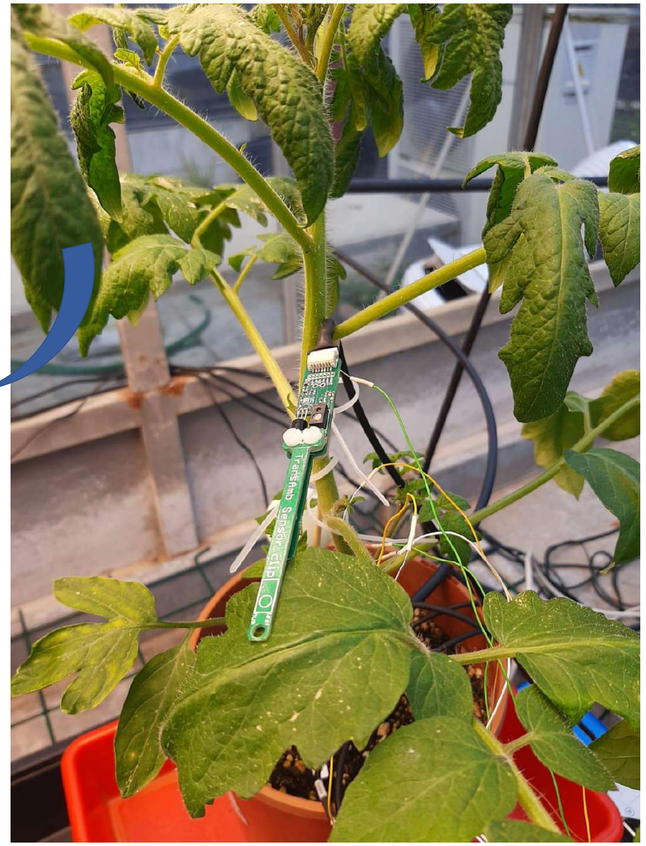
Compartir 19 Me gusta Twittear 10







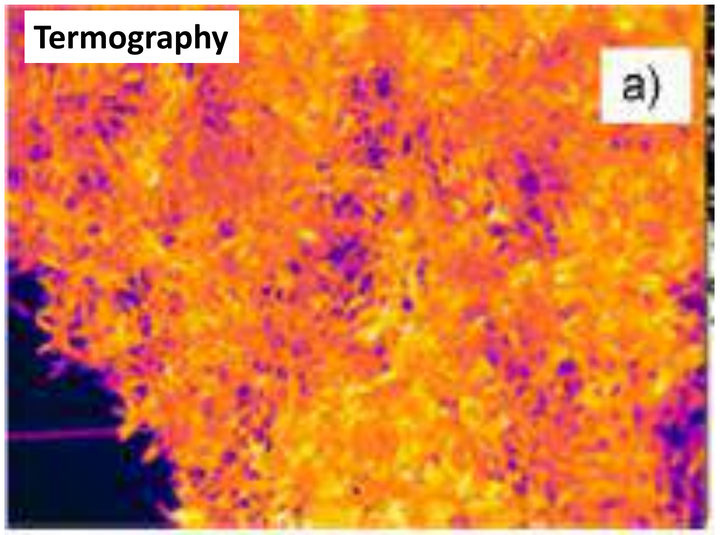




Descodificación → **Fisiología Vegetal**

Retrieving stomatal conductance from plant-based sensors

Termography



Agricultural Water Management 188 (2017) 50–60

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Assessing plant water status in a hedgerow olive orchard from thermography at plant level☆

I.F. García-Tejero[a,*], A. Hernández[a], C.M. Padilla-Díaz[b], A. Diaz-Espejo[b], J.E Fernández[b]

Agricultural Water Management 187 (2017) 210–221

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Research Paper

Assessing a crop water stress index derived from aerial thermal imaging and infrared thermometry in super-high density olive orchards

Gregorio Egea[a,*], Carmen M. Padilla-Díaz[b], Jorge Martinez-Guanter[a], José E. Fernández[b], Manuel Pérez-Ruiz[a]

Turgor-related probes



Agricultural and Forest Meteorology 272–273 (2019) 156–165

Contents lists available at ScienceDirect

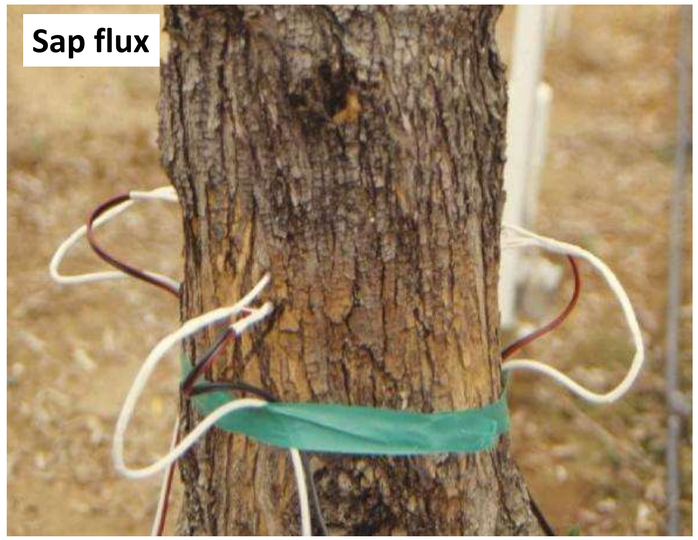
Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Sensitivity of olive leaf turgor to air vapour pressure deficit correlates with diurnal maximum stomatal conductance

C.M. Rodriguez-Dominguez[a,*], V. Hernandez-Santana[a], T.N. Buckley[b], J.E. Fernández[a], A. Diaz-Espejo[a]

Sap flux



Agricultural and Forest Meteorology 256–257 (2018) 458–469

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Relationships between fruit growth and oil accumulation with simulated seasonal dynamics of leaf gas exchange in the olive tree

V. Hernandez-Santana[a], R.D.M. Fernandes[a], A. Perez-Arcoiza[a], J.E. Fernández[a], J.M. Garcia[b], A. Diaz-Espejo[a,*]

Agricultural and Forest Meteorology 218–219 (2016) 92–101

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

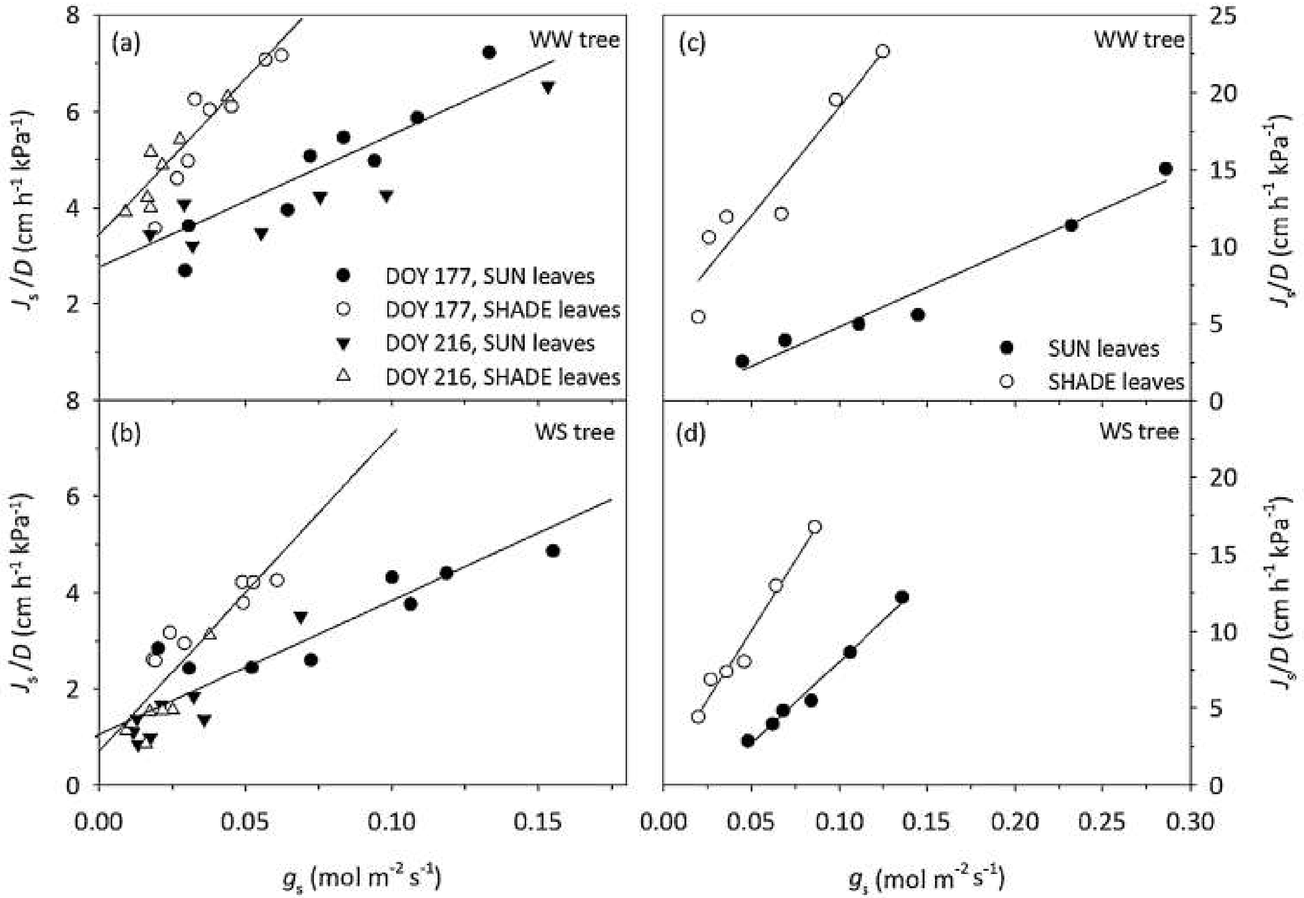
The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit

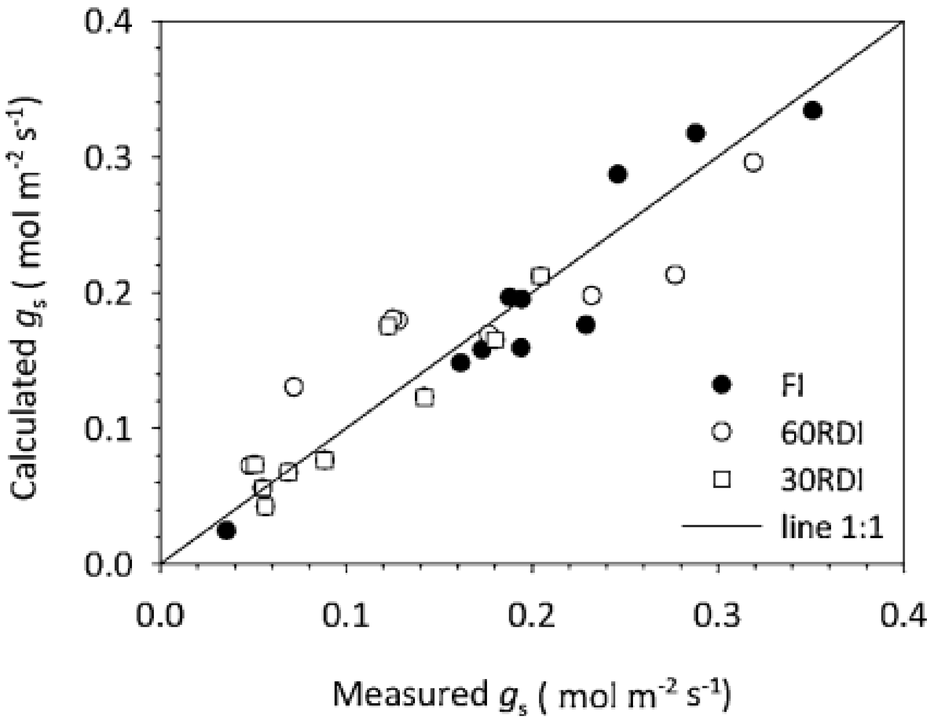
V. Hernandez-Santana[a], J.E. Fernández[a], C.M. Rodriguez-Dominguez[a,b], R. Romero[a], A. Diaz-Espejo[a,*]

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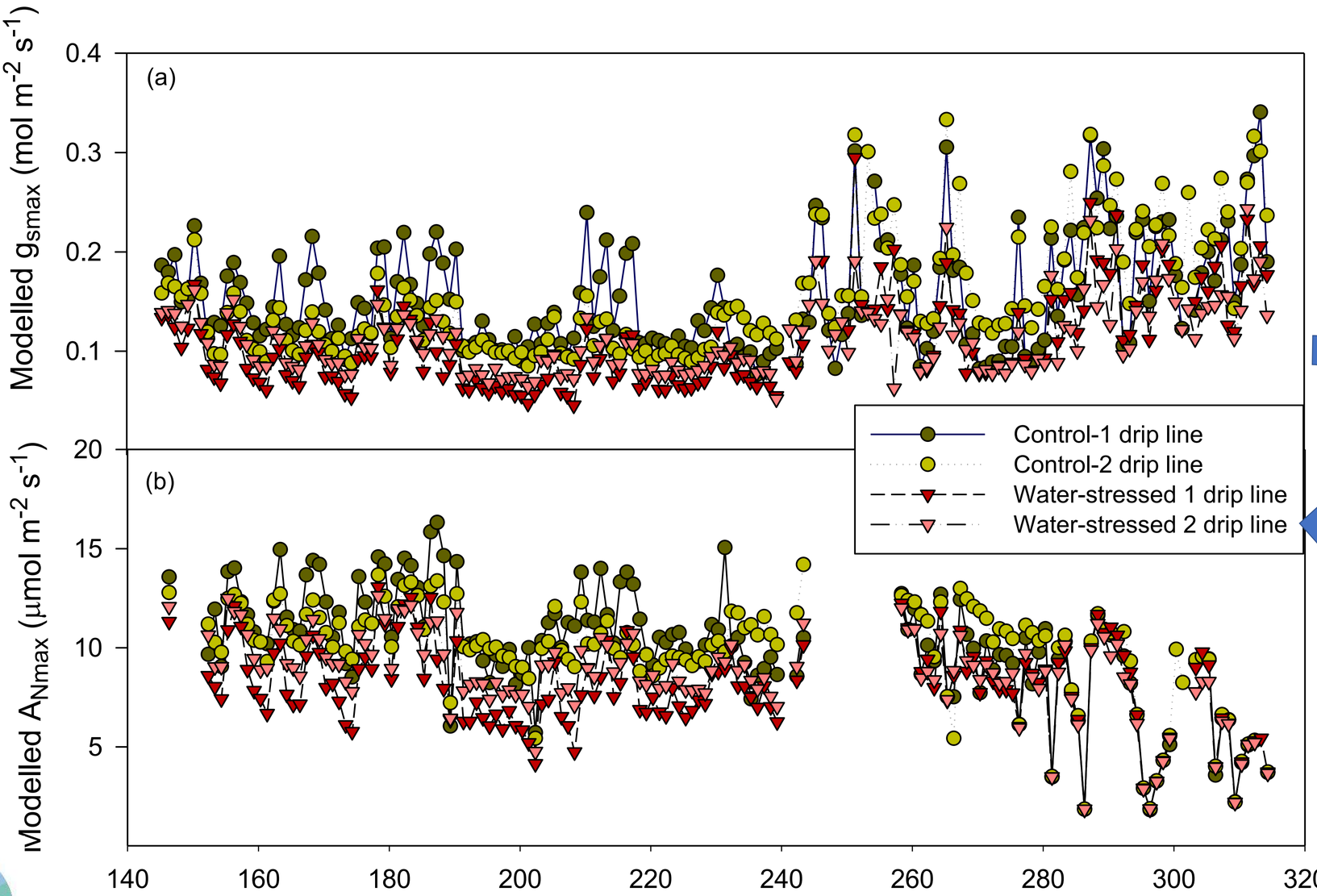
Can we really estimate g_s automatically? The case of sap flow

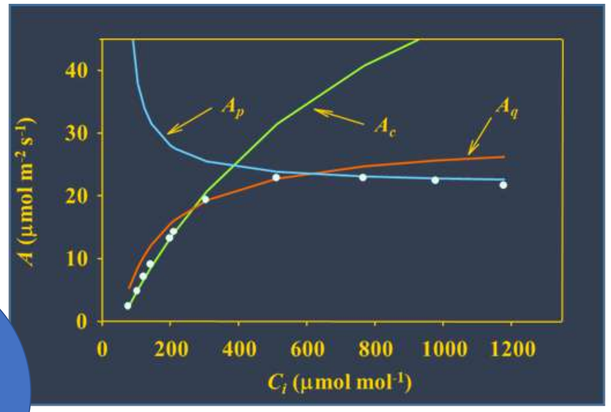




Hernandez-Santana et al. 2016

Done! Now we can estimate stomatal conductance and photosynthesis in continuous in the field





Farquhar et al. model

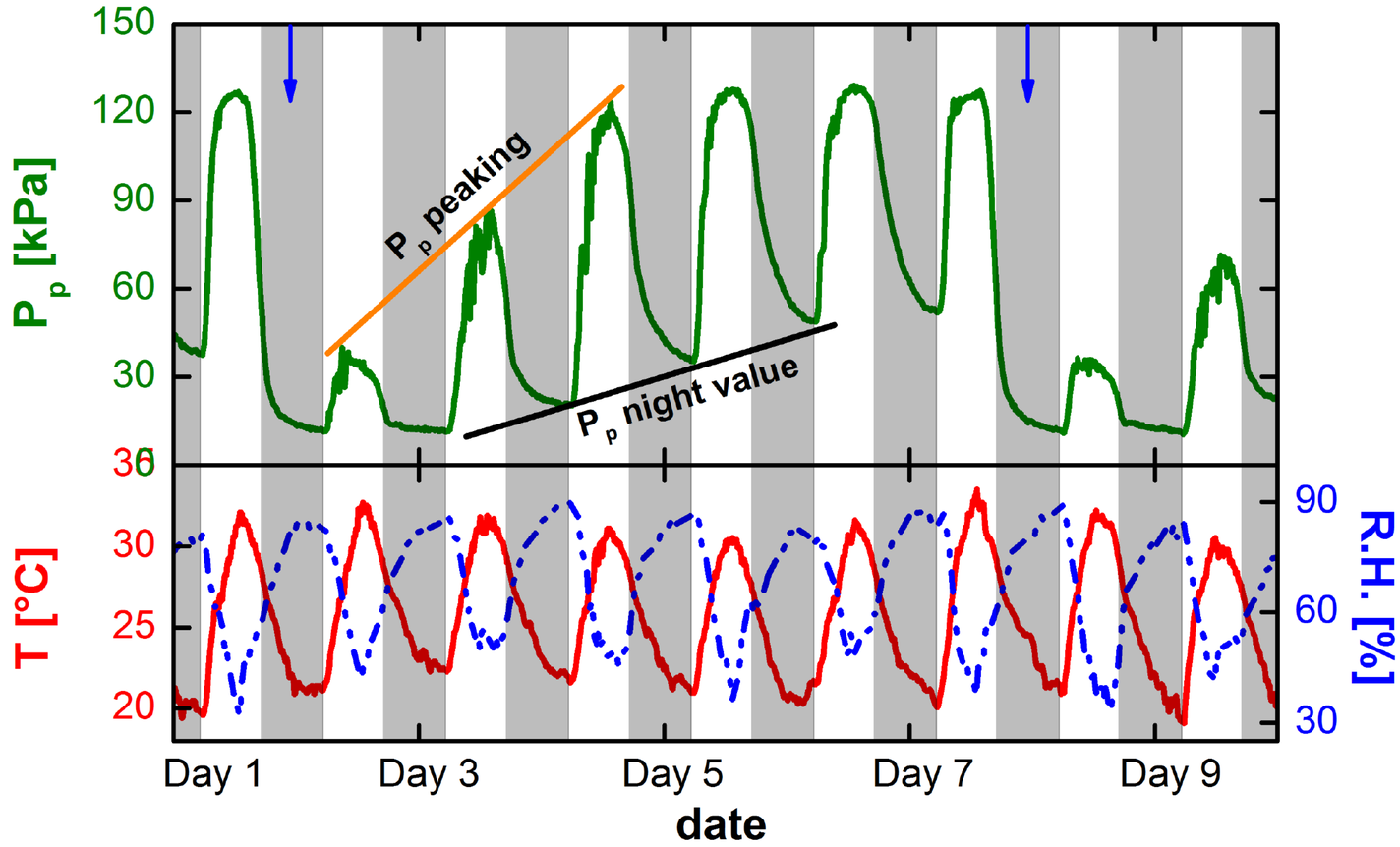
Hernandez-Santana et al. 2018

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Can we really estimate g_s automatically? The case of the turgor-related probes





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Can we really estimate g_s automatically? The case of the turgor-related probes

Cell water relations

$$P = \psi_{leaf} + \pi$$

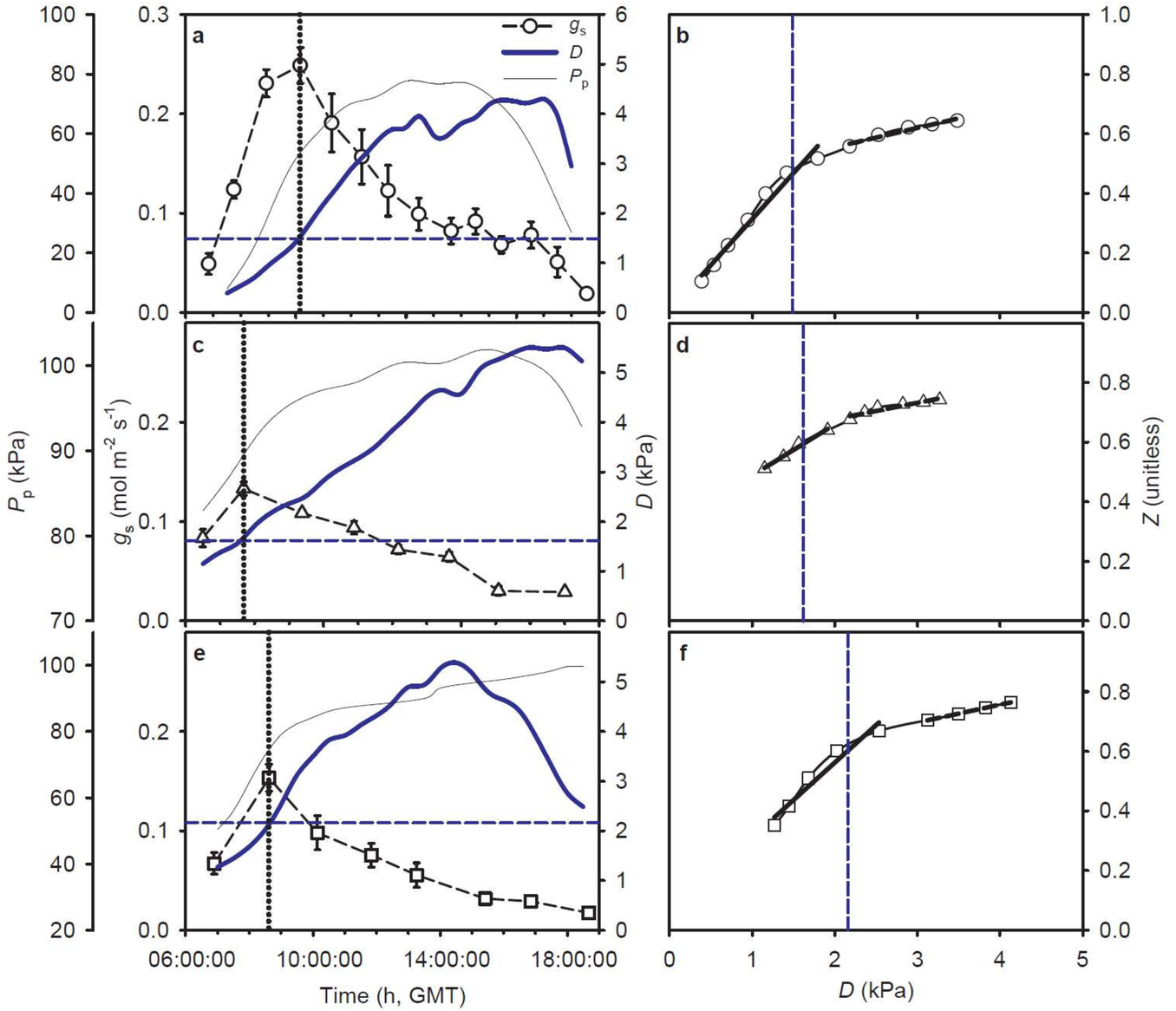
Ohm´s law analogy

$$\psi_{leaf} = \psi_{soil} - \frac{g_s D}{K}$$

$$P = \psi_{soil} + \pi - \frac{g_s D}{K}$$

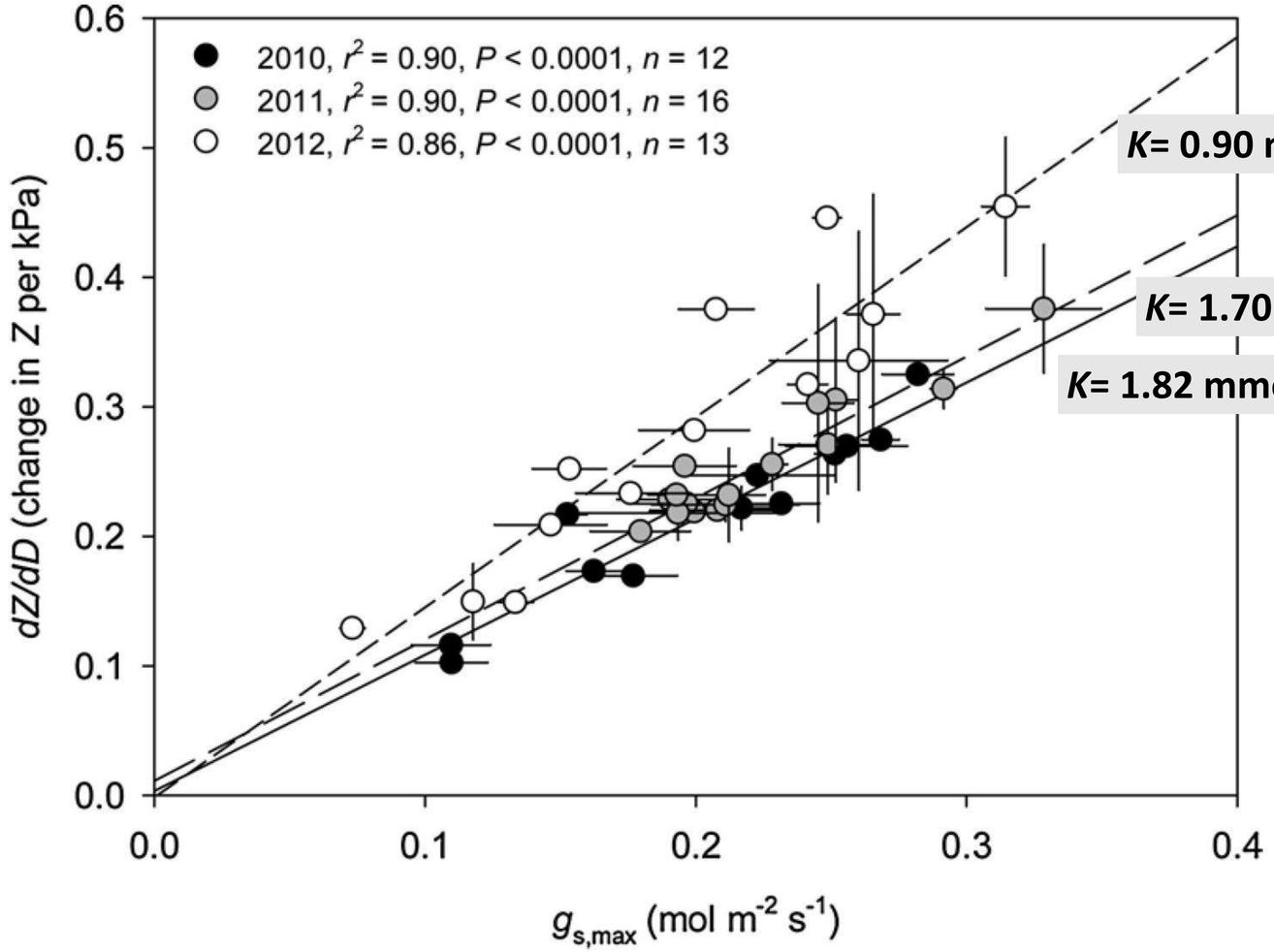
$$\frac{dP}{dD} = -\frac{g_s}{K}\left(1 + \frac{d \ln g_s}{d \ln D}\right)$$

$$\frac{dP}{dD} = -\frac{g_{s,max}}{E_{max}}$$



Rodriguez-Dominguez et al. 2019

Can we really estimate g_s automatically? The case of the turgor-related probes



***K*= 0.90 mmolm^{-2}s^{-1}**

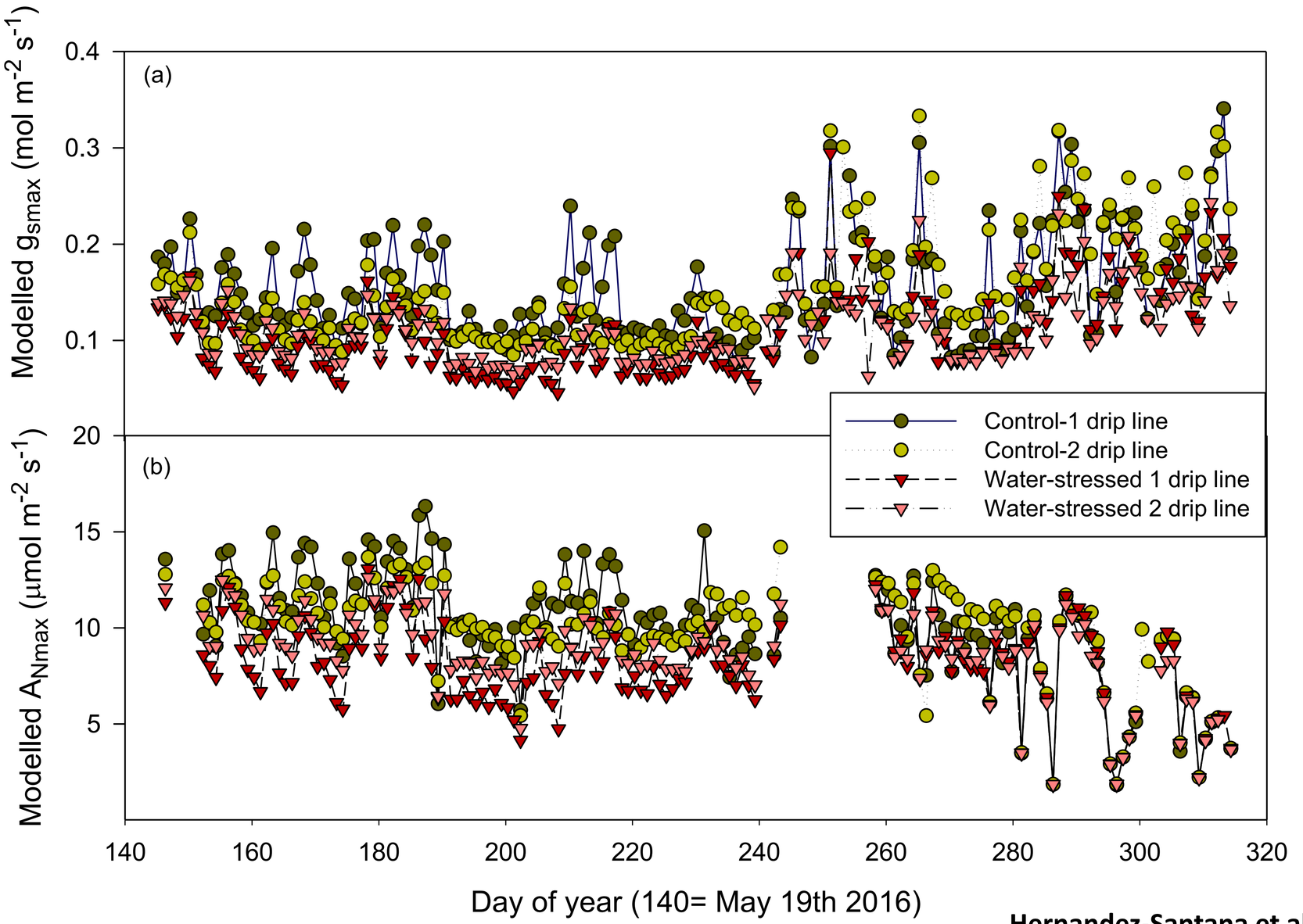
***K*= 1.70 mmolm^{-2}s^{-1}**

***K*= 1.82 mmolm^{-2}s^{-1}**

$$\frac{dP}{dD} = -\frac{g_s}{K}\left(1 + \frac{d \ln g_s}{d \ln D}\right)$$

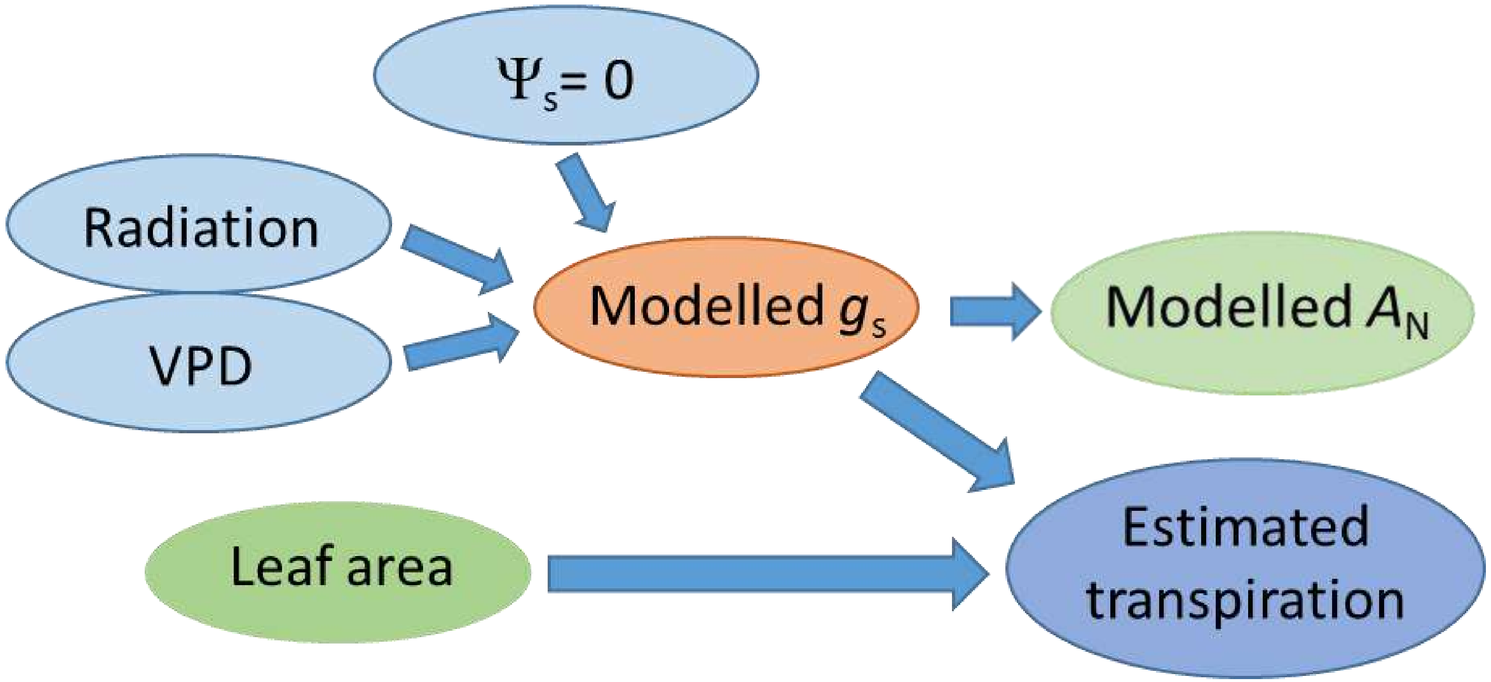
Rodriguez-Dominguez et al. 2019

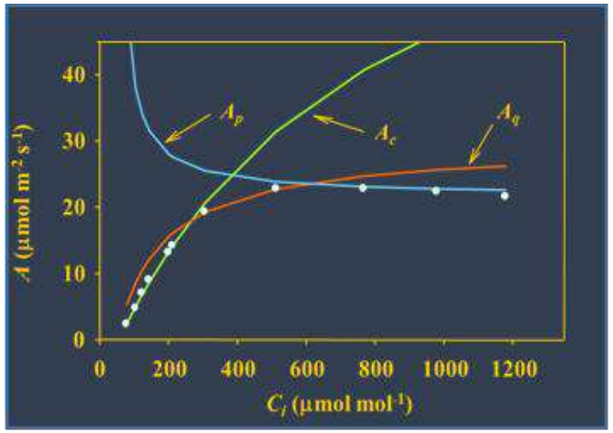
Can we really estimate g_s automatically? The case of the turgor-related probes



Hernandez-Santana et al. 2017

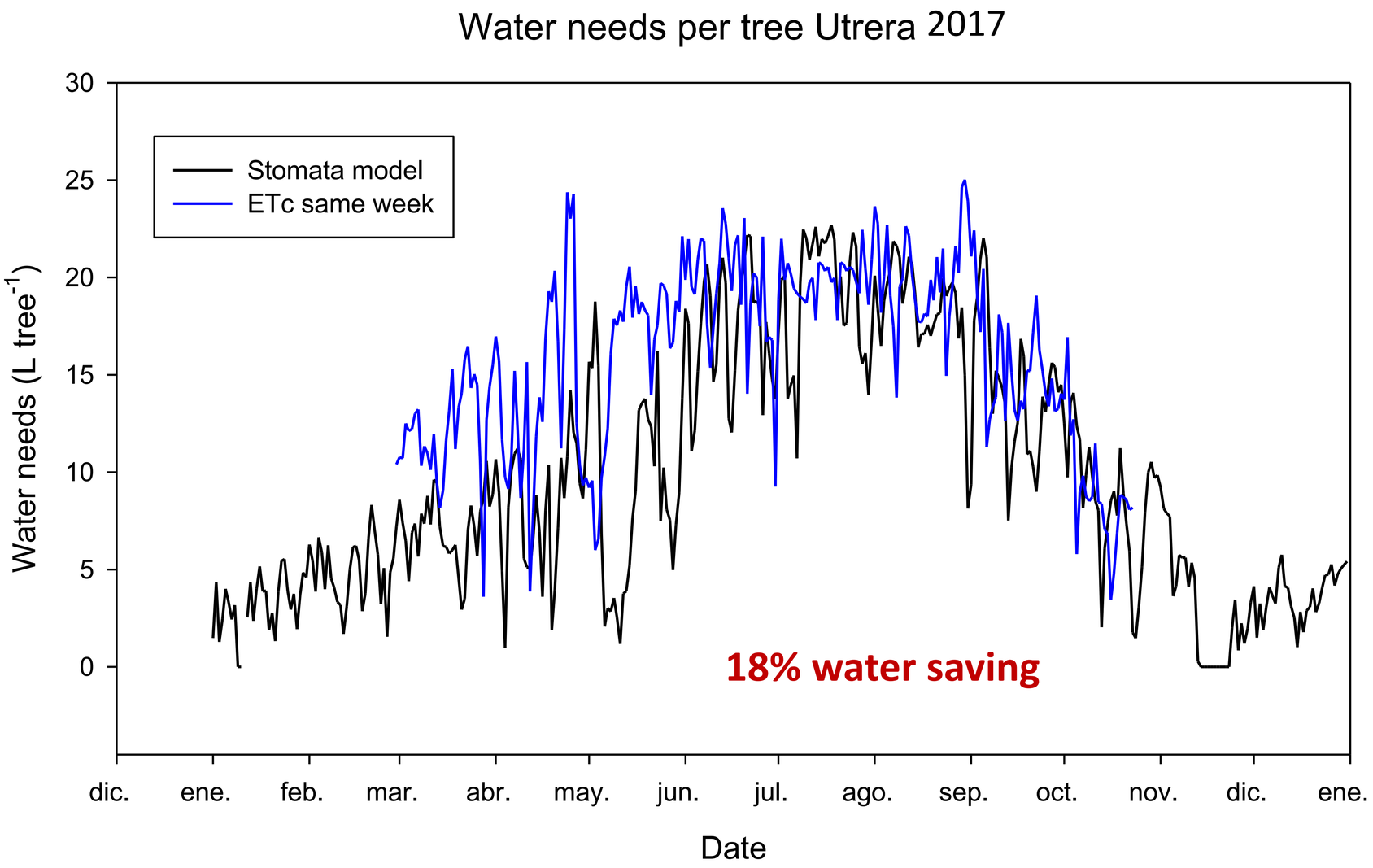
Translating the theory to reality: simplying further the estimation of stomatal conductance





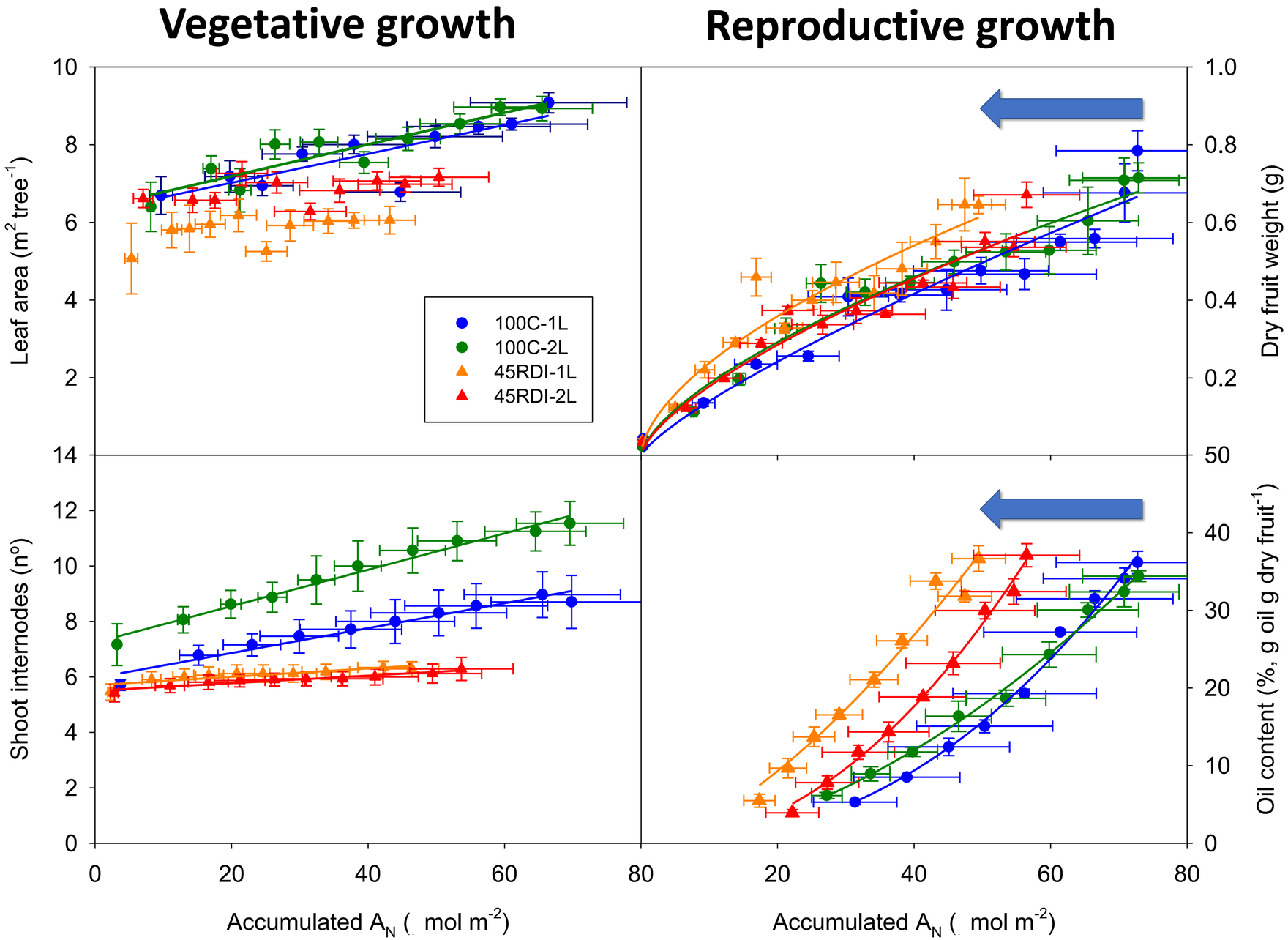
Farquhar et al. model

Can we apply a method based on stomatal conductance?



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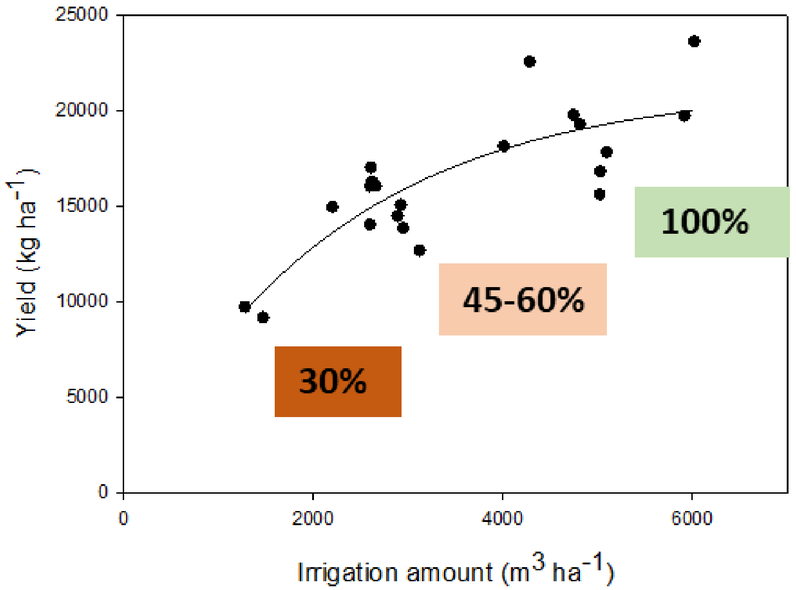
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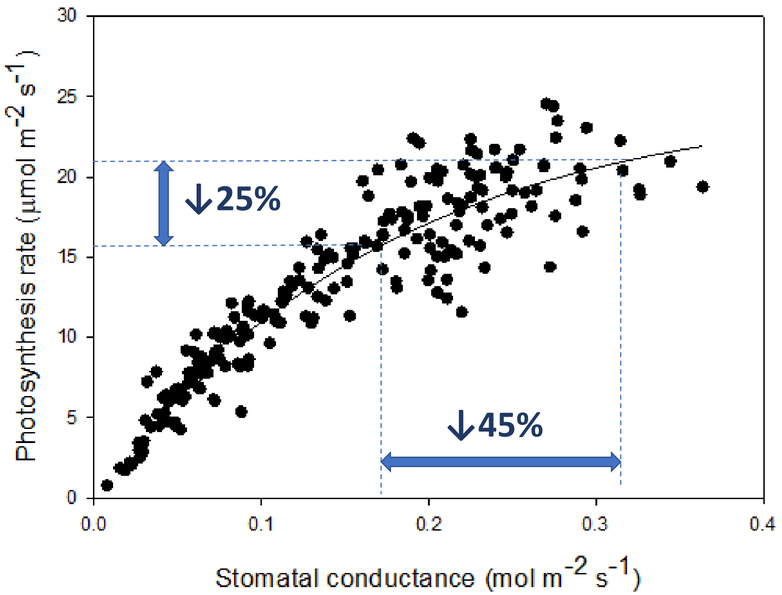
Hernandez-Santana et al. 2018

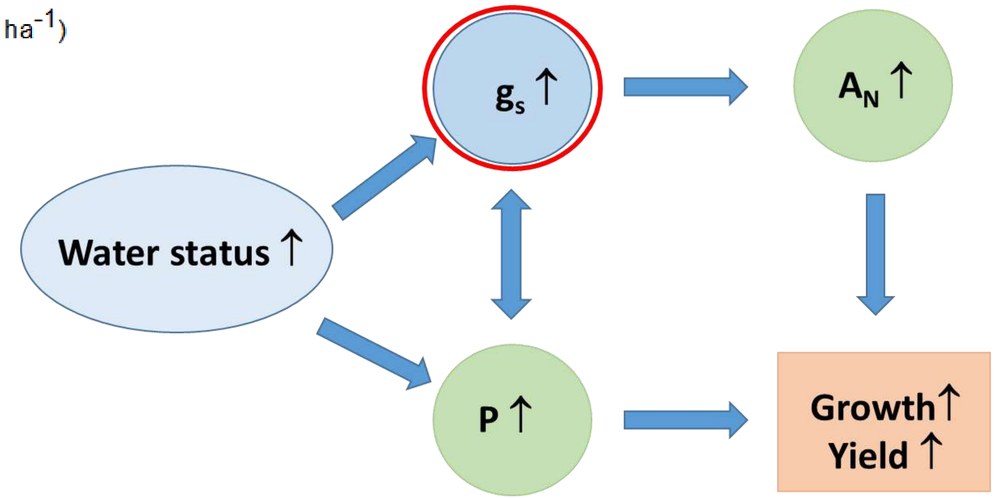
A new approach: the novel plant-based method

Conceptual basis

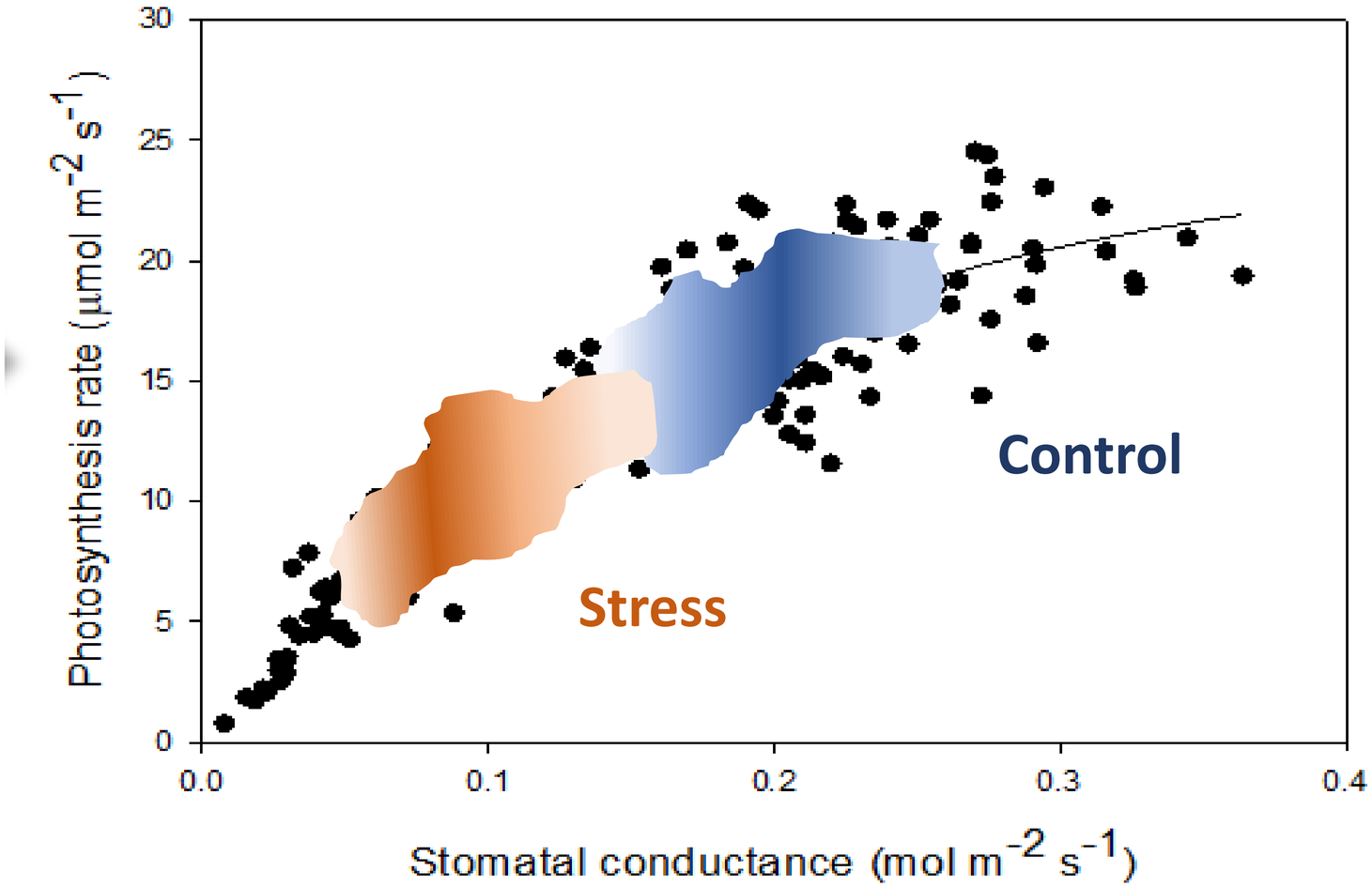


Analogous??





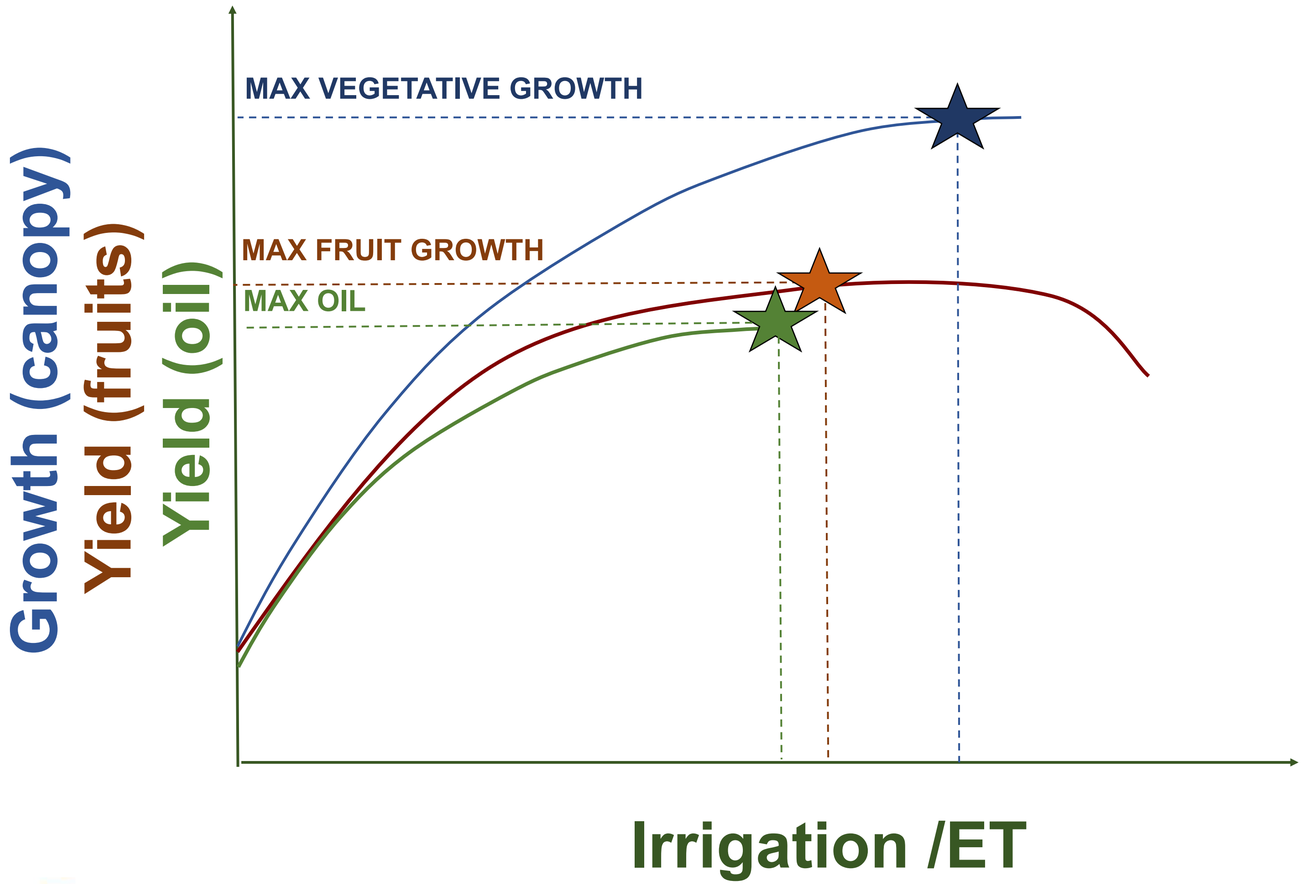
“Where” have my plants been “working”?

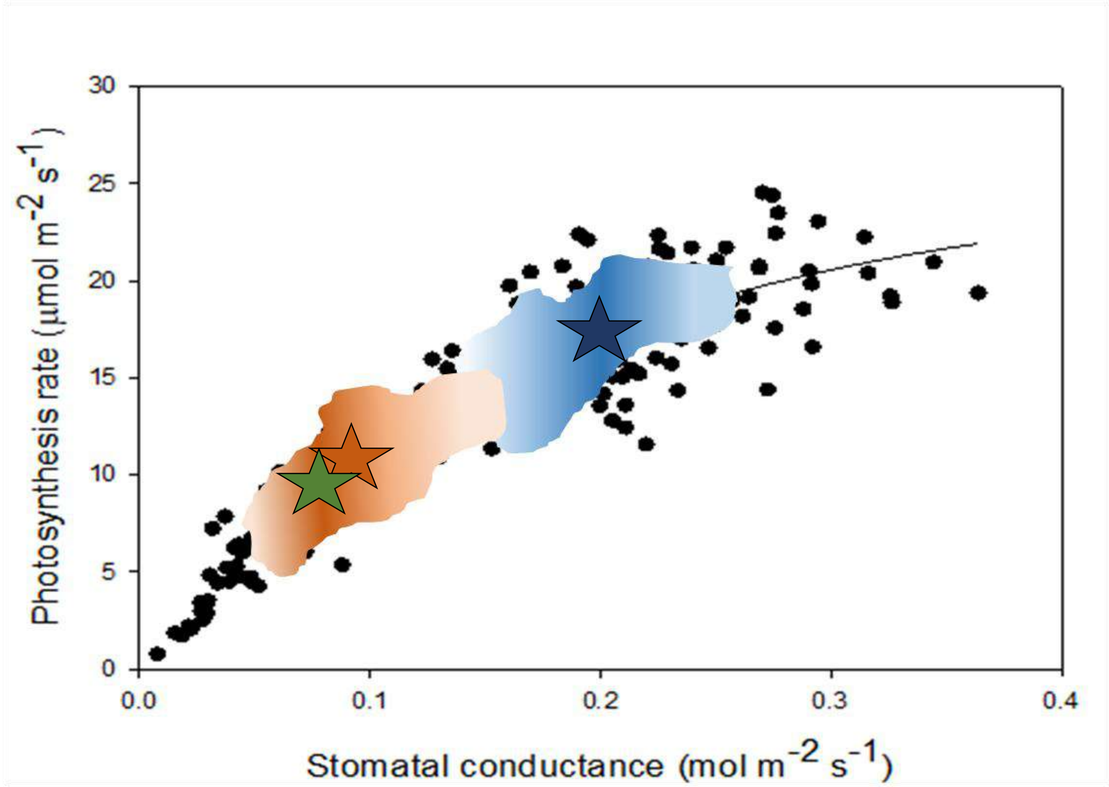


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Vegetative and reproductive processes have different sensitivities





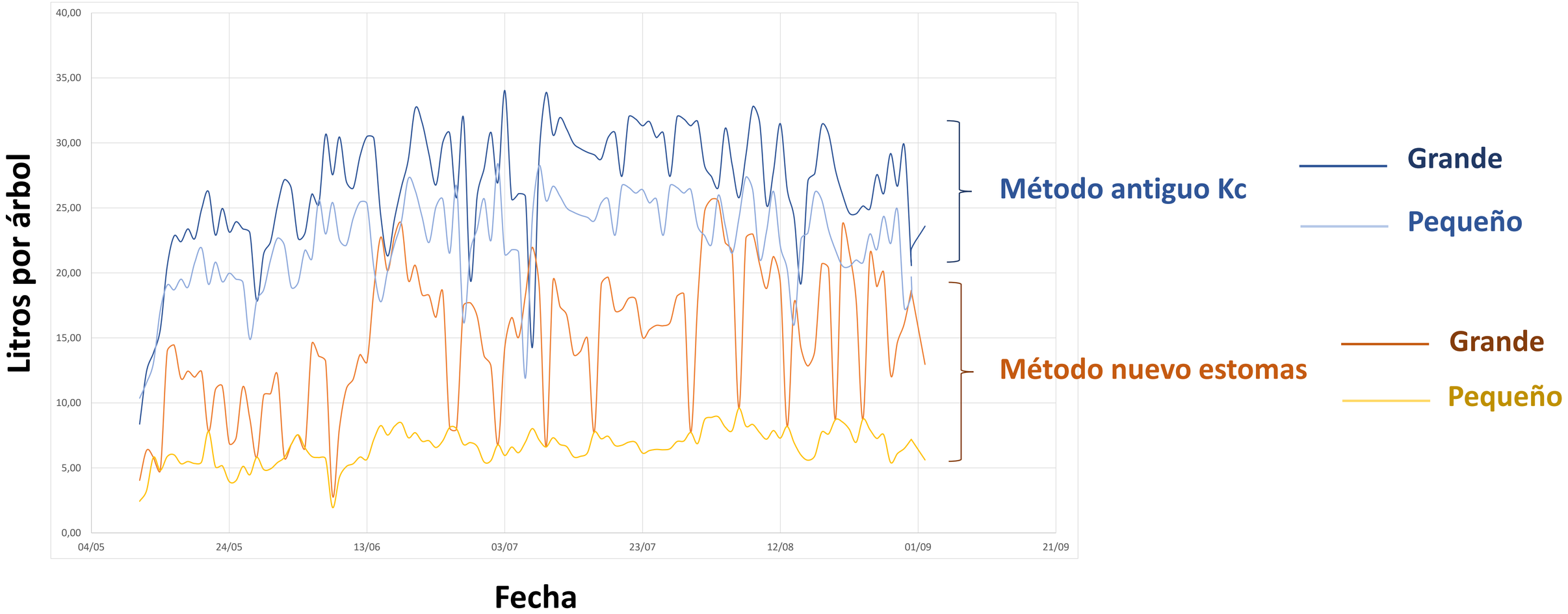
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Some agronomical results

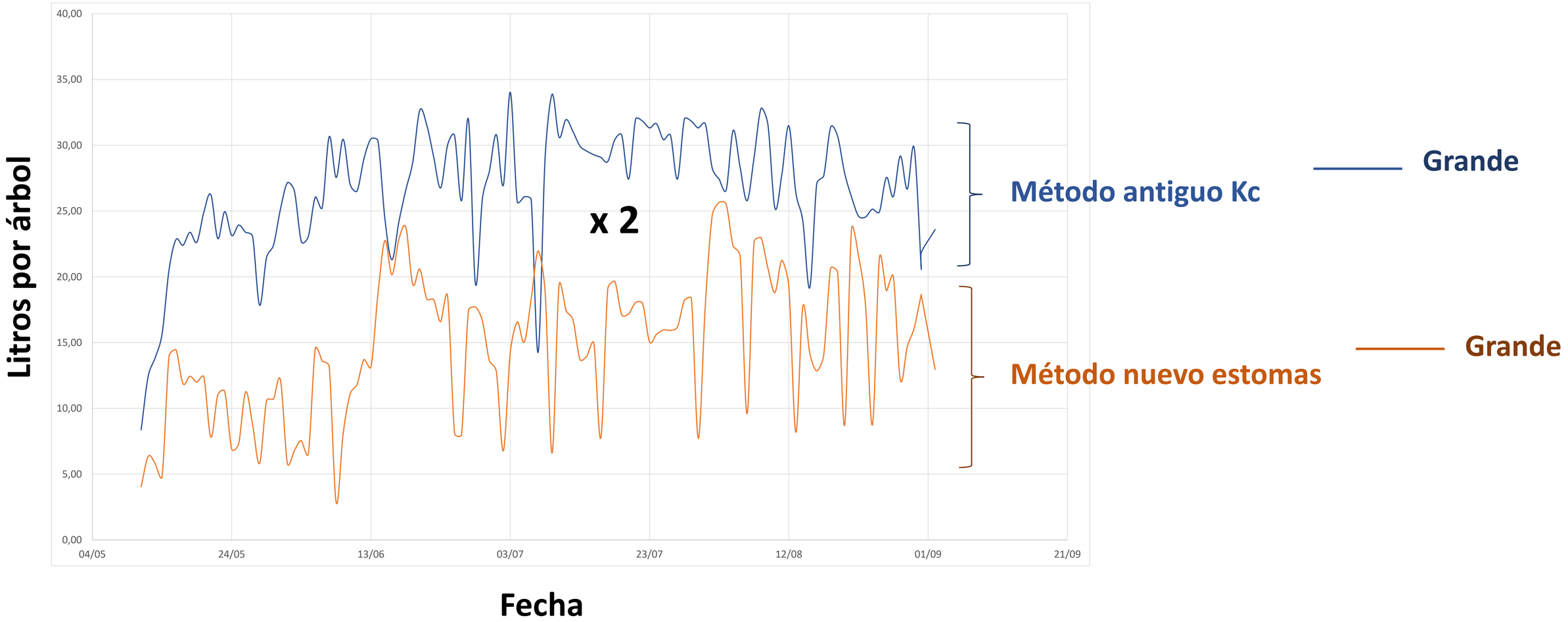
Resultados preliminares del método nuevo basado en los estomas

Cálculo de riego limoneros

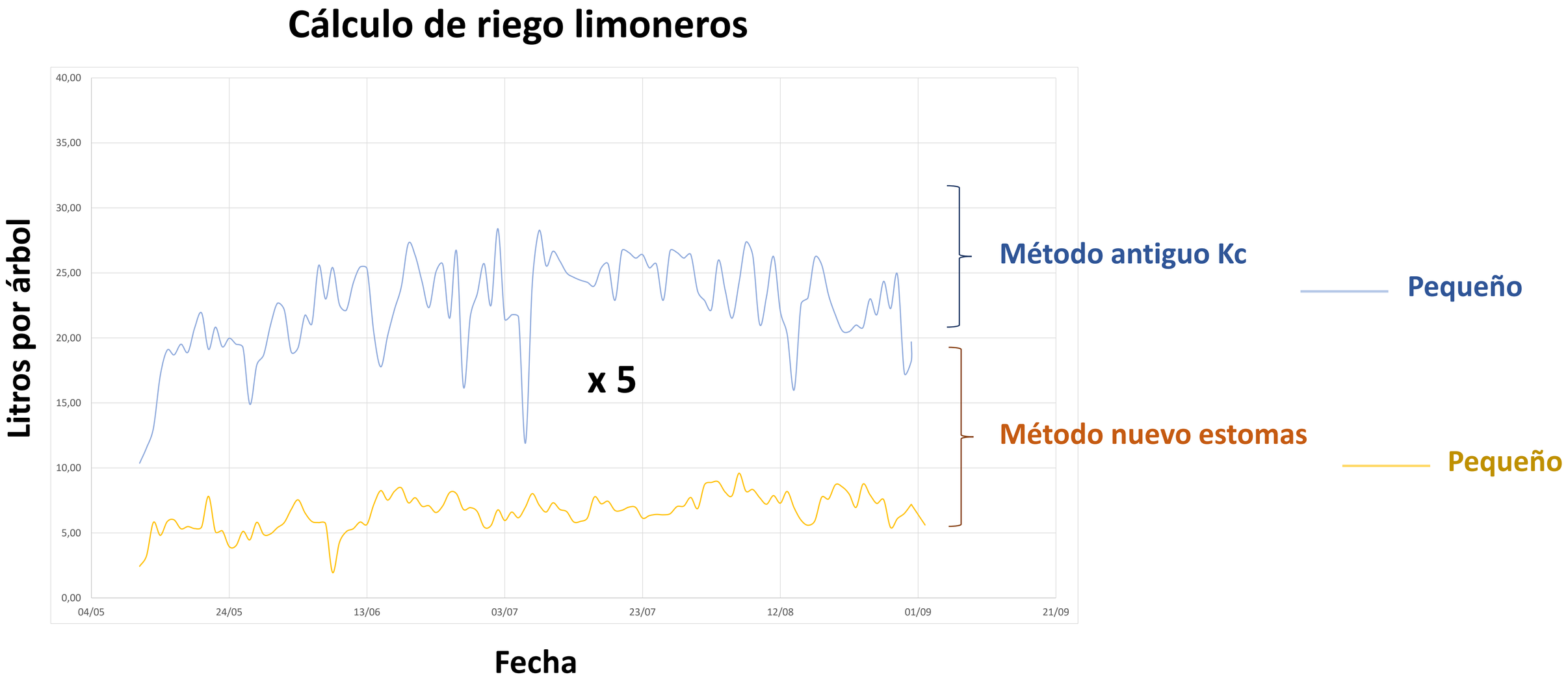


¿Qué diferencias hay entre los métodos?

Cálculo de riego limoneros

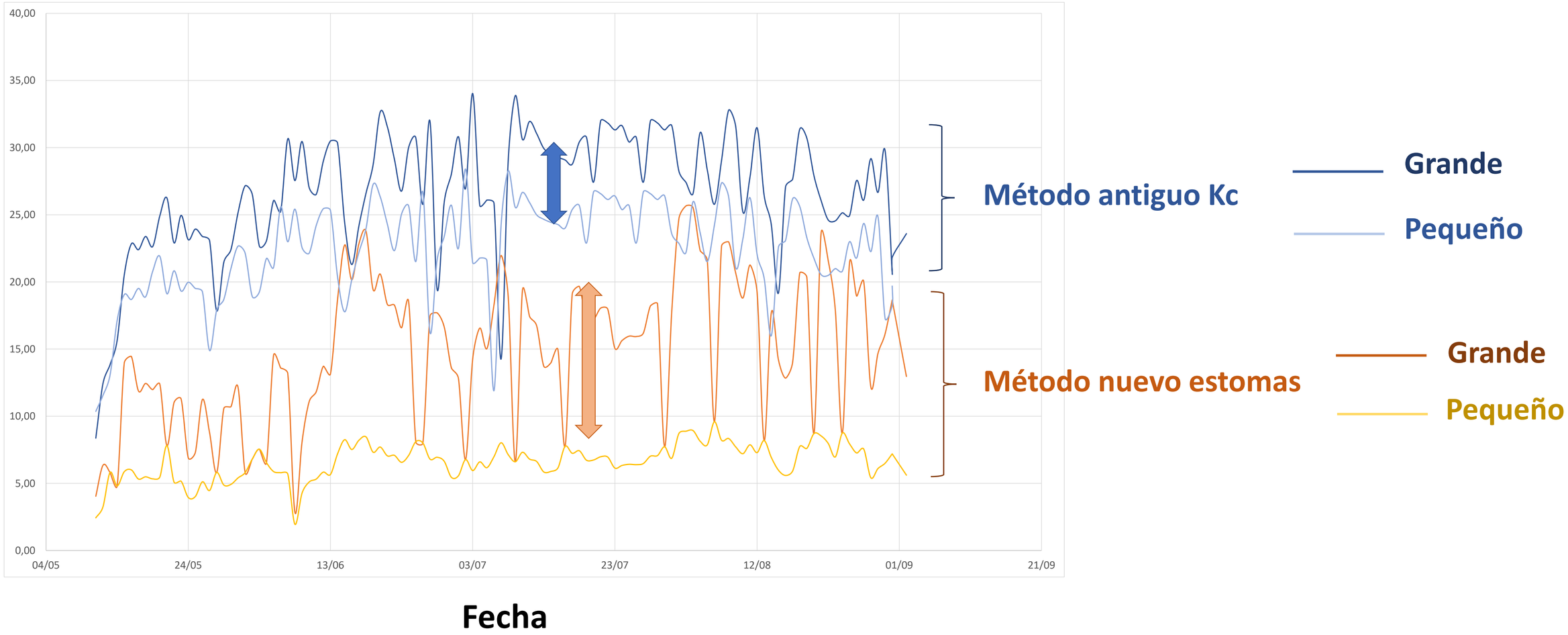


¿Qué diferencias hay entre los métodos?

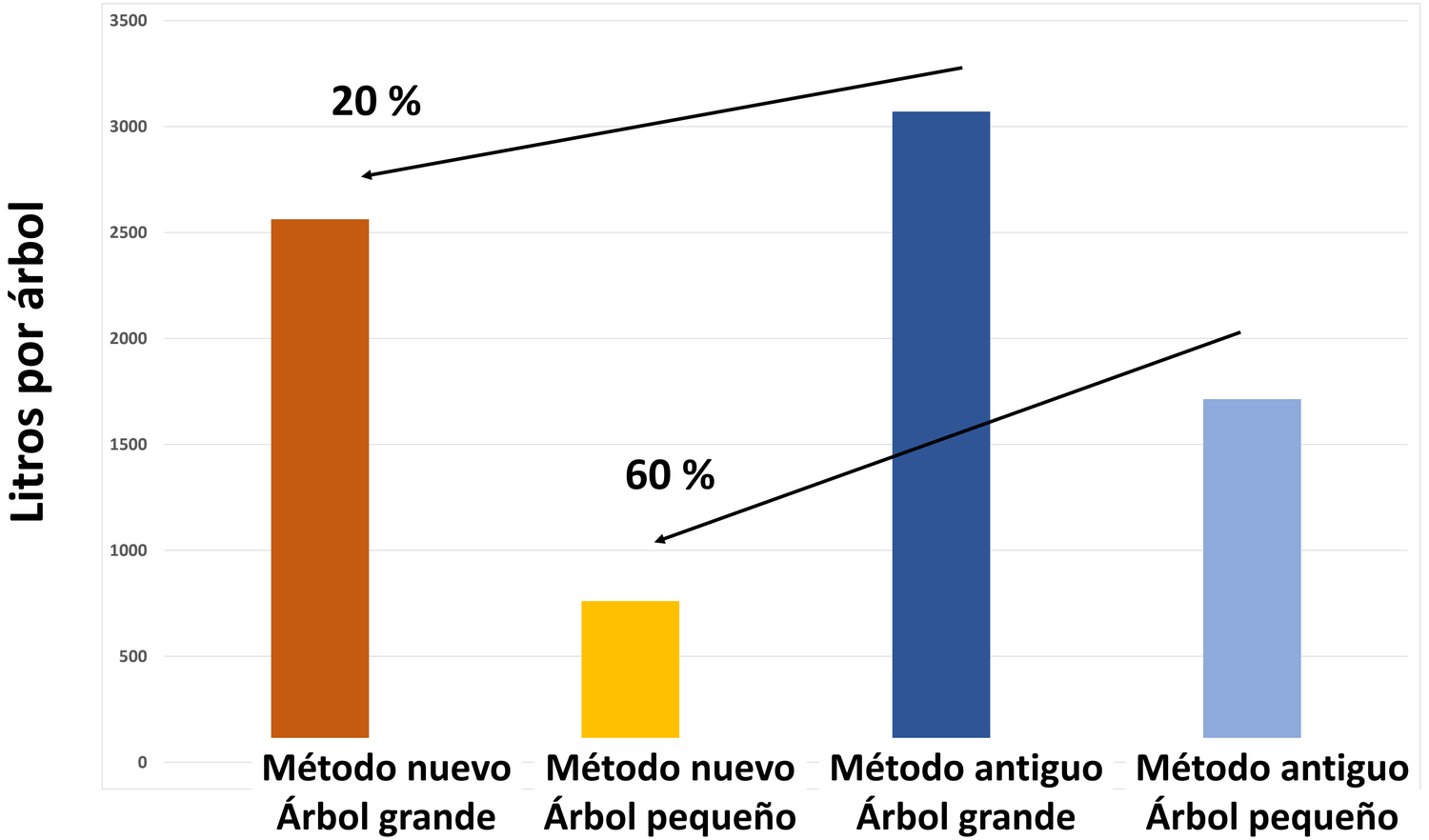


Resultados preliminares del método nuevo basado en los estomas

Cálculo de riego limoneros



Consumos de agua del periodo para cubrir necesidades totales



Pilot farms: Murcia (Spain)





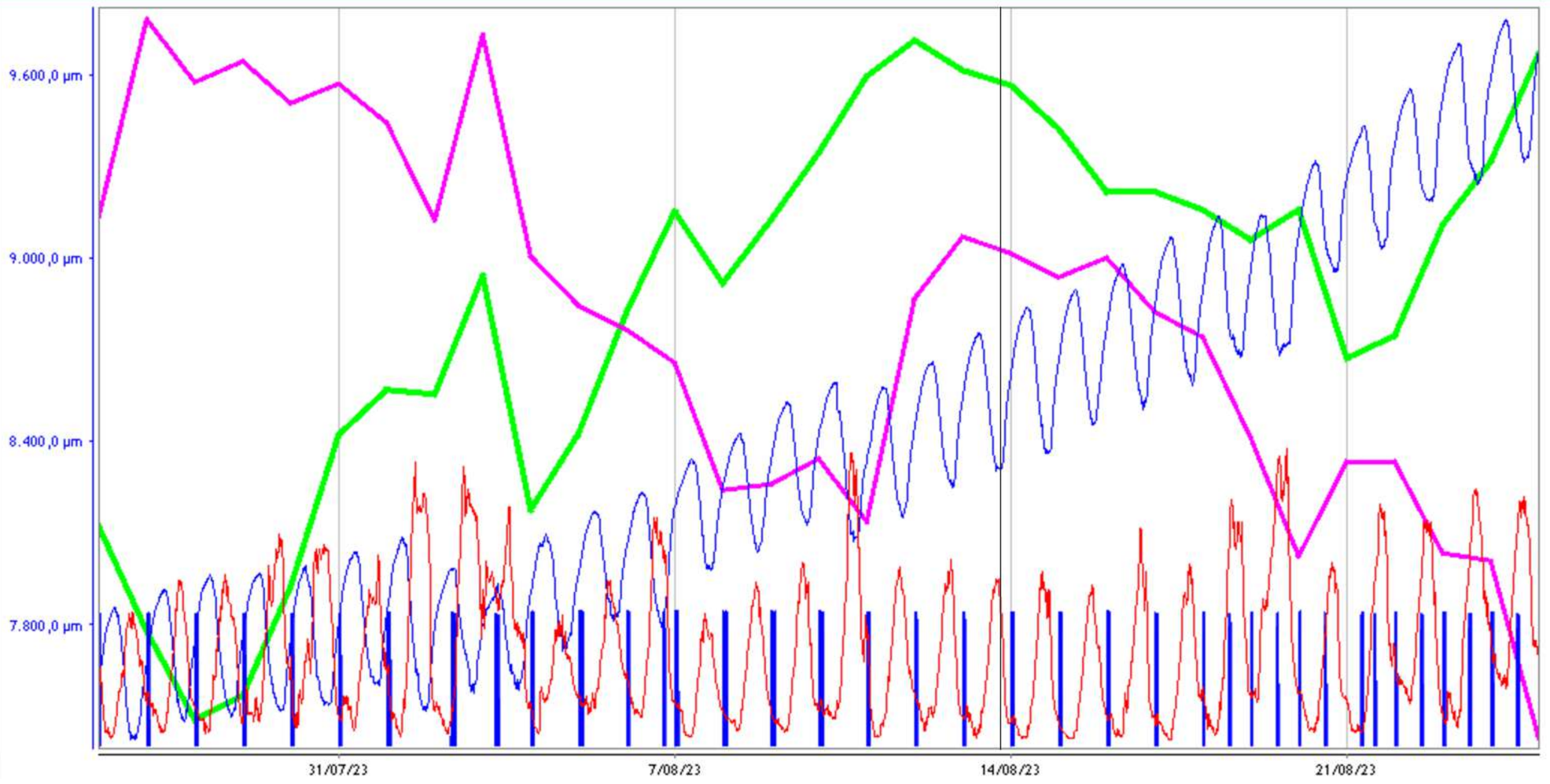
- Fruit tree: lemon orchard var. Seedless
- 20 ha
- Drip irrigation

ADCON TELEMETRY | addVANTAGE Pro 6.4
The next level of visualisation

Herramientas | Ventana | Ayuda | Desconexión

26 de julio de 2023 | 30 Días

- Suma
  67,44 vol%
  (25-ago-2023 0:45:00)
- Promedio Raices
  11,17 vol%
  (25-ago-2023 0:45:00)
- Promedio Drenaje
  11,58 vol%
  (25-ago-2023 0:45:00)
- PROMEDIO Nitrato 30 c
  -497,3 mV
  (24-ago-2023 23:59:00)
- PROMEDIO Nitrato 70 c
  -422,8 mV
  (24-ago-2023 23:59:00)
- PROMEDIO Potasio 70cn
  403,3 mV
  (24-ago-2023 23:59:00)
- PROMEDIO Potasio 30cn
  377,7 mV
  (24-ago-2023 23:59:00)
- Pressure absolute
  1,8 bar
  (25-ago-2023 0:45:00)
- Precipitation
  0,0 mm



HOW TENDENCIES OF DPV max, Gs, dendrometer, IVEG and irrigation are coherent

MUNDOSOL SPAIN

	Gs		dendrometer		R SENSING
	P2-stress	DPVmax	Dgrowth	IRRIGATION	IVEG
09/06/2022 7:00	0,114	2,9			53
10/06/2022 7:00	0,114	3,6			
11/06/2022 7:00	0,109	3,9			
12/06/2022 7:00	0,087	4,4			
13/06/2022 7:00	0,072	4,7			
14/06/2022 6:00	0,060	5,2			54
15/06/2022 7:00	0,067	4,5			
16/06/2022 8:30	0,059	5,4			
17/06/2022 7:00	0,055	5,7			
18/06/2022 8:00	0,058	5,3			
19/06/2022 7:00	0,068	3,4			54
20/06/2022 6:30	0,091	3,5			
21/06/2022 7:00	0,093	3,5			
22/06/2022 8:00	0,087	3,1			
23/06/2022 7:00	0,082	3,4			
24/06/2022 9:30	0,077	3,1			56
25/06/2022 11:30	0,070	4,2			
26/06/2022 7:00	0,080	3,2			
27/06/2022 15:00	0,084	3,6			
28/06/2022 7:30	0,096	2,7			
29/06/2022 8:00	0,103	3,2			59
30/06/2022 7:00	0,096	2,6			

COLORS:

- Irrigation
- the stomata is more open or increase of dendrometer
- 1º day of stress
- 2º day of stress
- 3º and more days os stress



Cuadro 6. Se marcan con colores de naranja a rojo y marrón las tendencias de aumento de estrés, ya sea por cierre estomático, por decrecimiento de tronco o por aumento de DPV max y también por no regar. En verde se ponen tendencias de menos estrés, es decir aumentos de apertura de estomas, crecimiento de tronco, bajada de DPV max y en azul riegos. Se observa unas tendencias coherentes, suficientes para que el agricultor tenga alertas

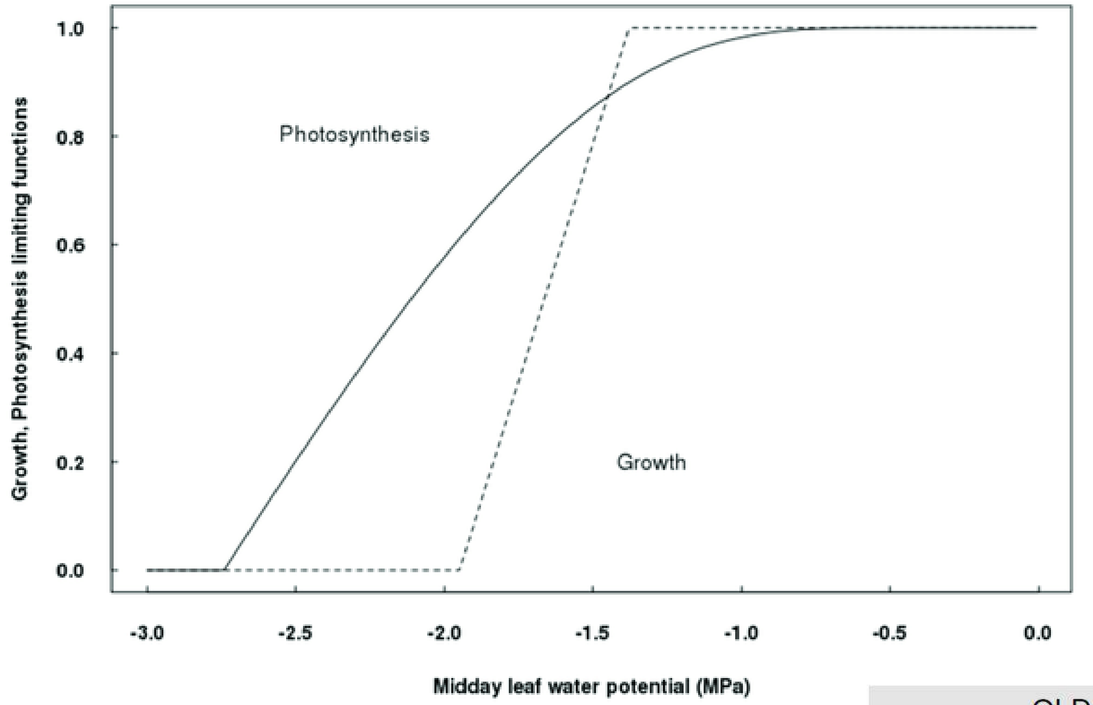
PRIMA
PARTNERSHIP FOR RESEARCH AND INNOVATION
IN THE MEDITERRANEAN AREA

IRRIWELL

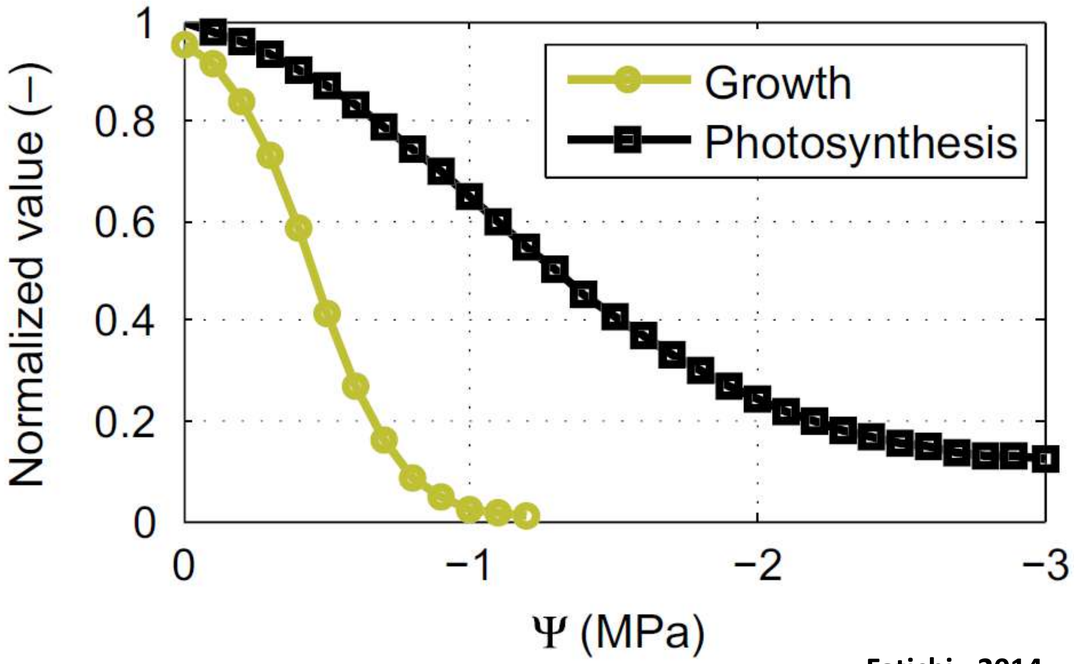
RESULTADOS		2023	2022
AGUA	IRRIWELL	79%	68%
	FARM		
NITRATO	IRRIWELL	86%	167%
	FARM		
POTASIO	IRRIWELL	123%	203%
	FARM		
PRODUCCION	IRRIWELL	388%	131%
	FARM		



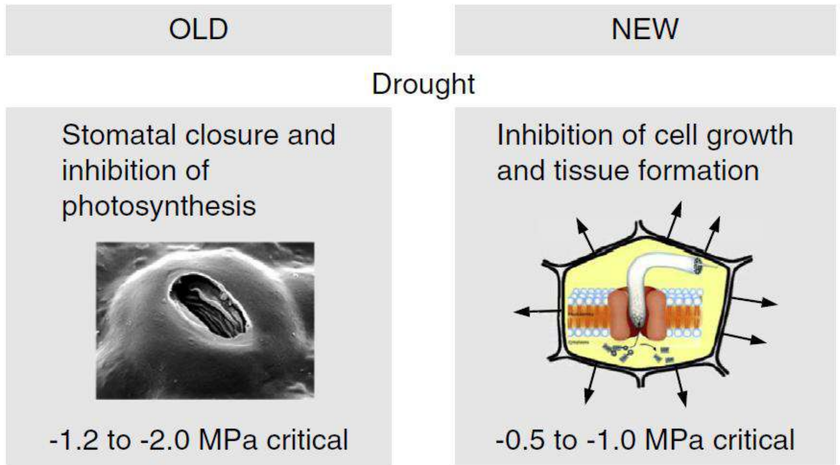
Controversial candidacy to rule growth over: support on sink



Rahmati et al., 2018

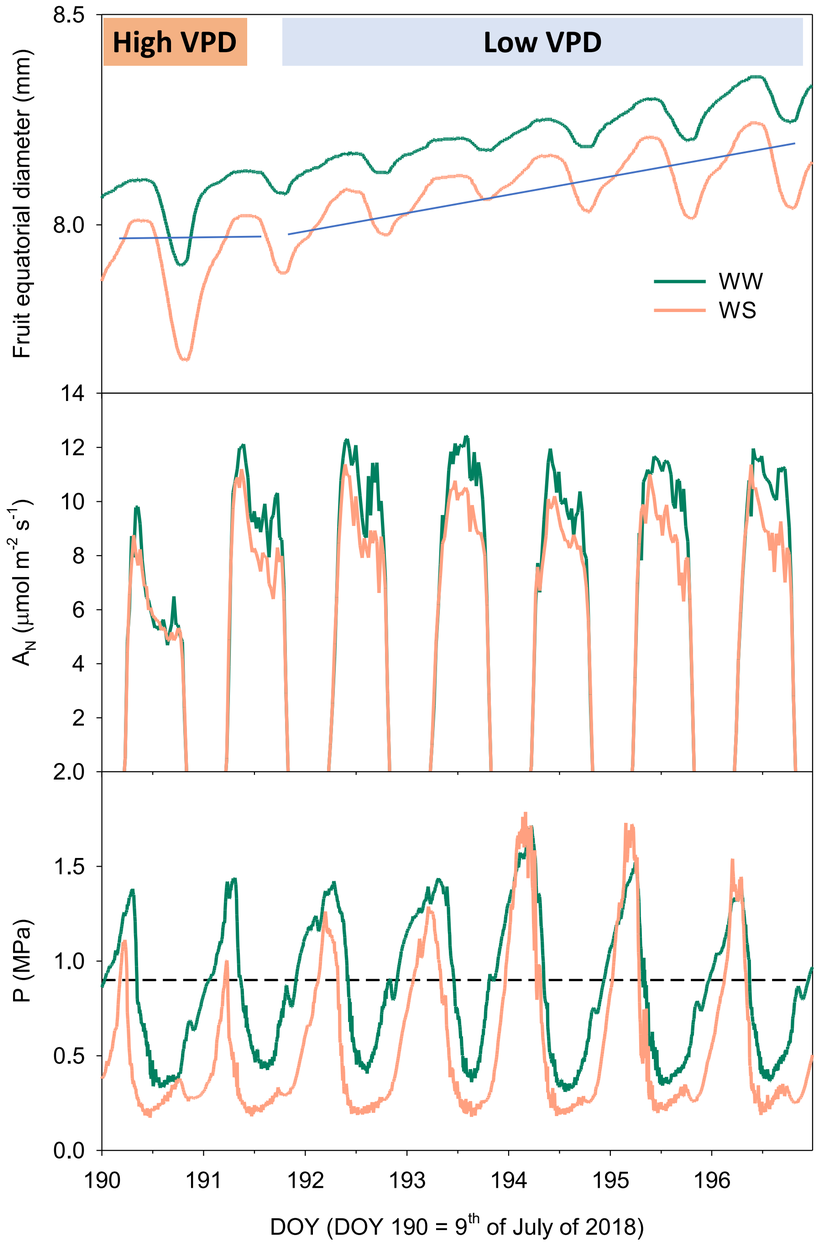


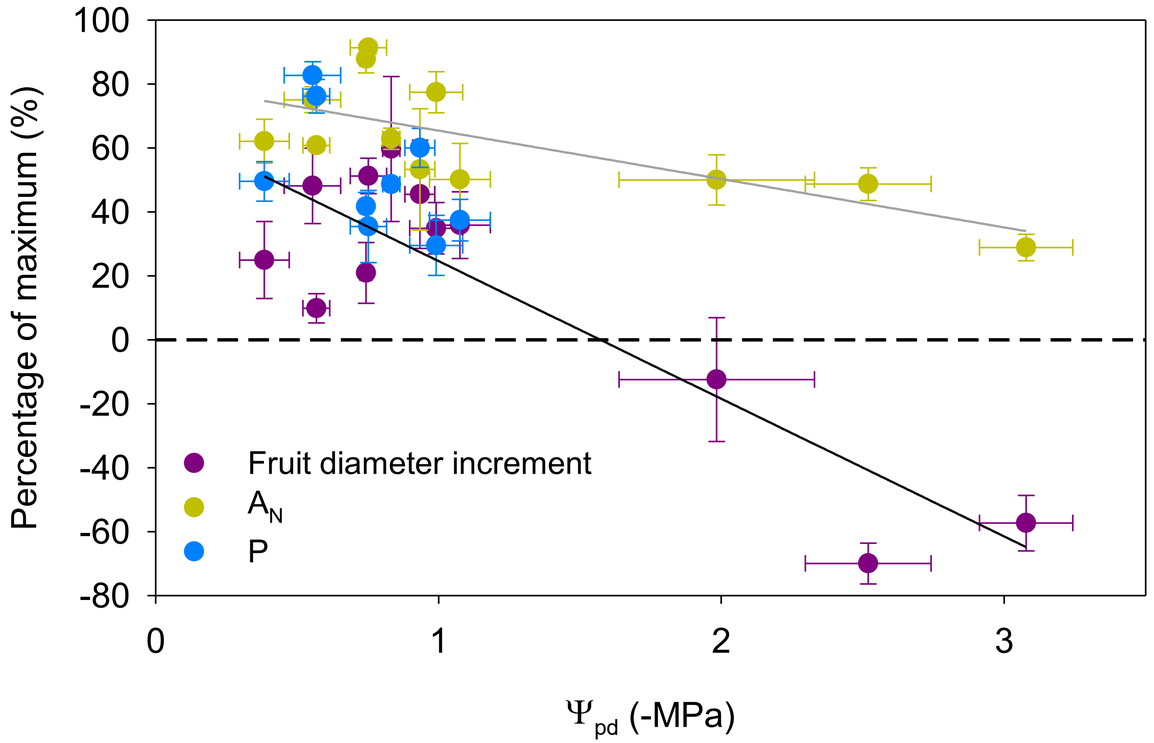
Fatichi., 2014



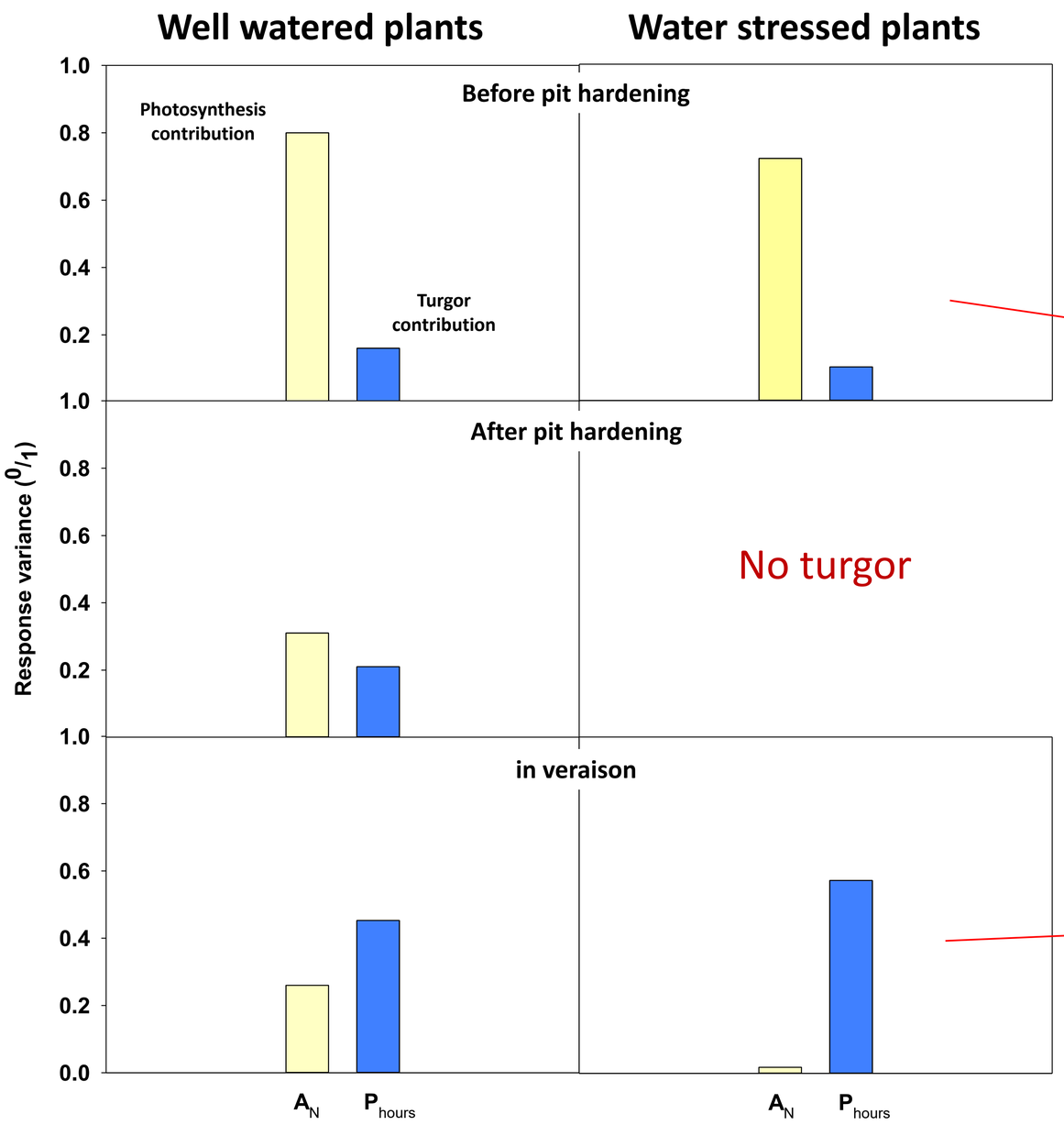
Korner, 2015

Growth, photosynthesis and turgor

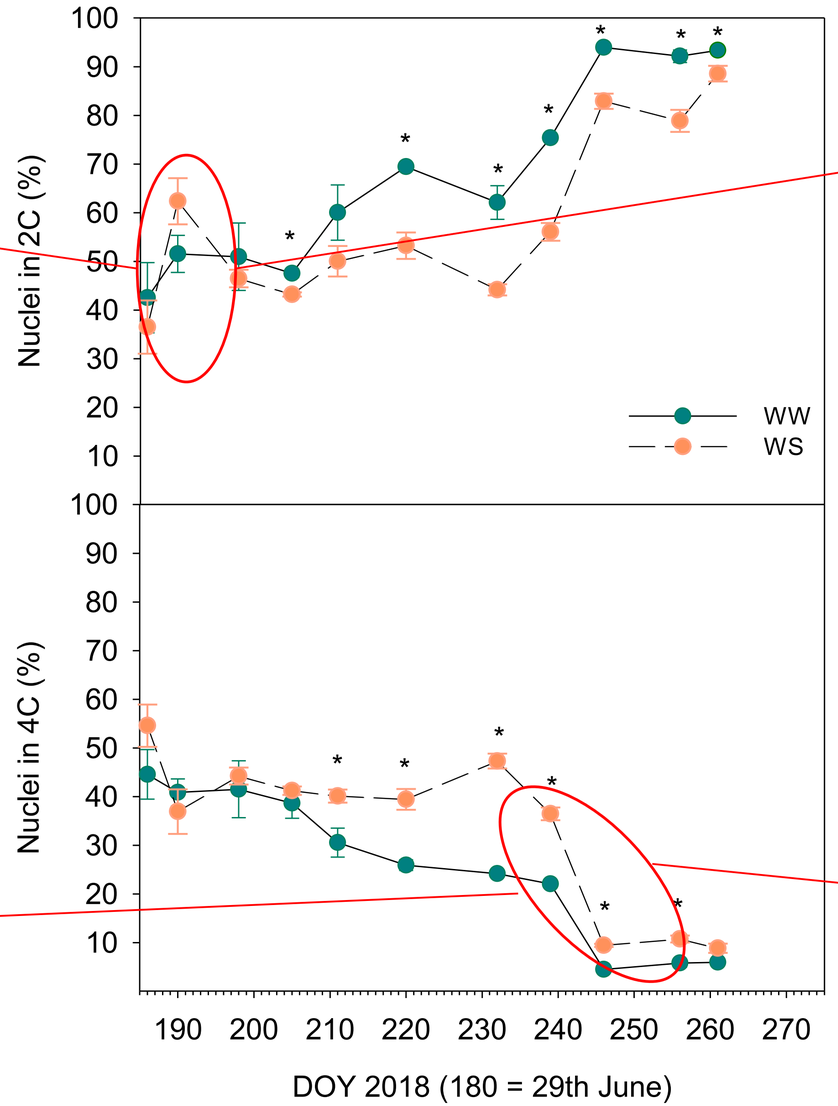




Both photosynthesis and turgor play a role



Flow Cytometry to detect cell division



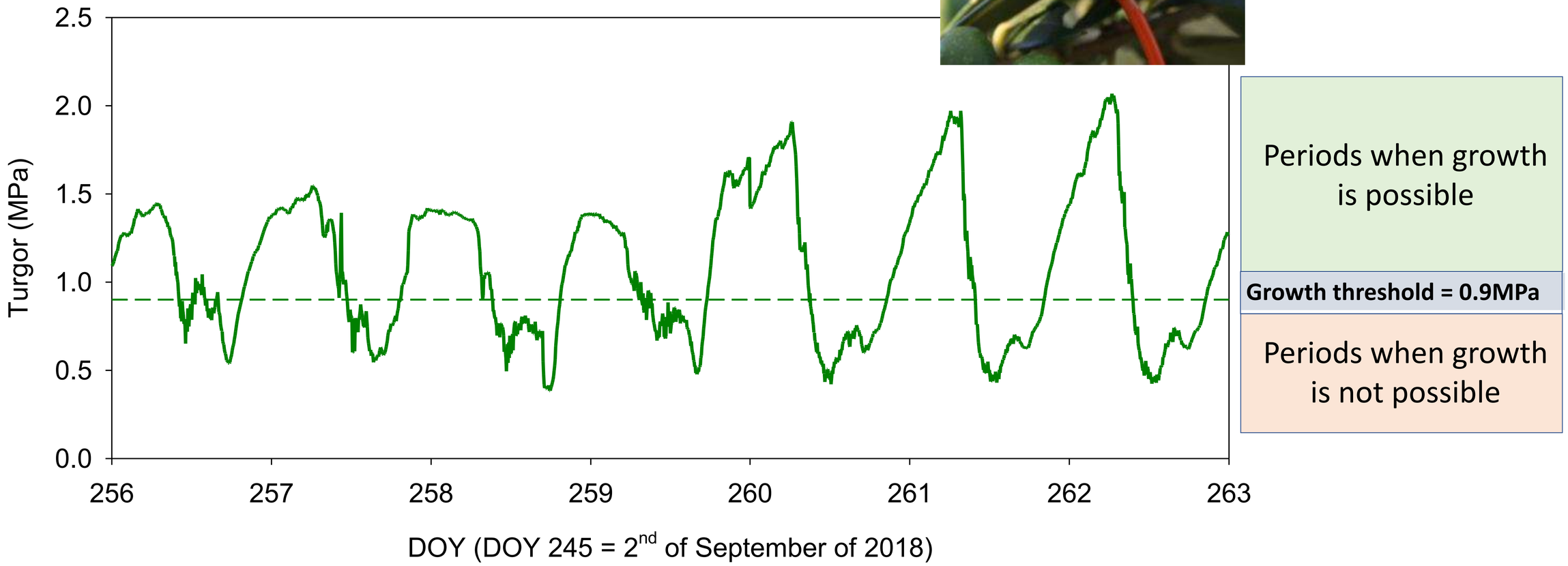
Cell division stage

Cell elongation stage

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Measuring in the field the sink strength: turgor





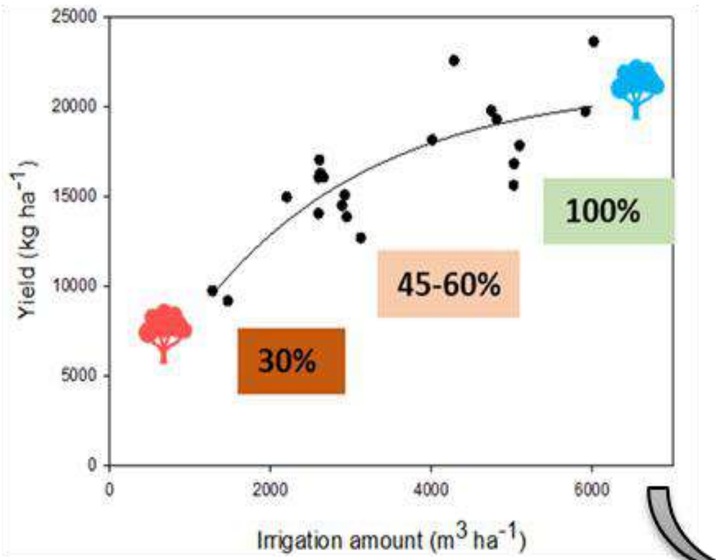
Growth turgor threshold from Lockhart´s seminal works (1965)
Genard et al. (2001) determined for woody species 0.9 MPa

IRNAS

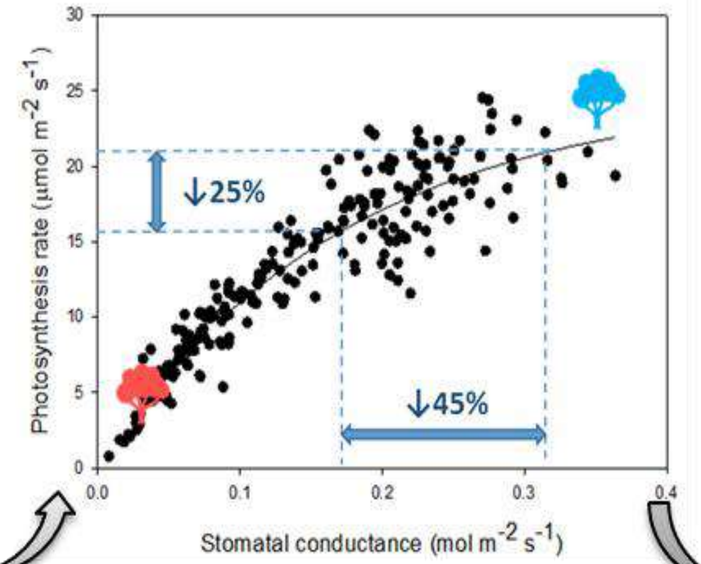
CSIC
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New approach based on turgor hours under evaluation

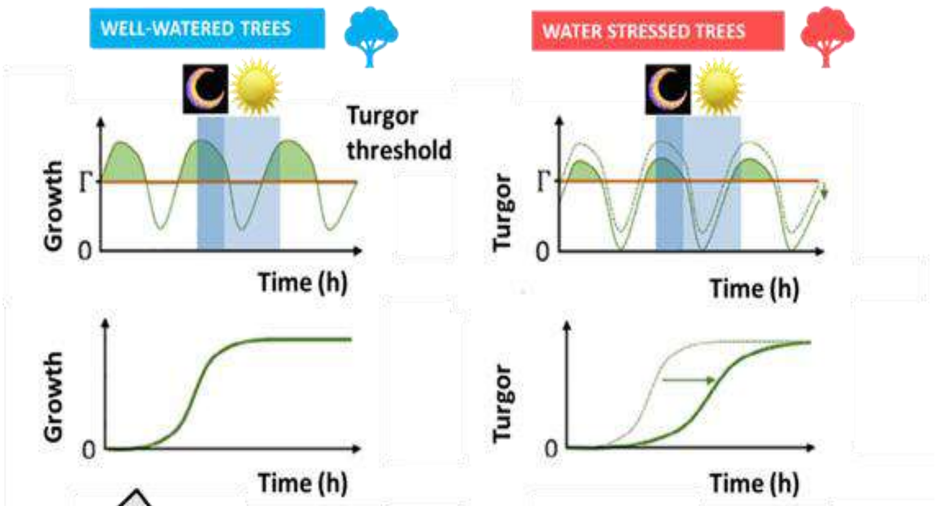
Classical yield response



REC proposal based on photosynthesis



TurGro proposal based on the sink limitation





NITRATE AND POTASSIUM PROBE

The first soil nutrition management tool



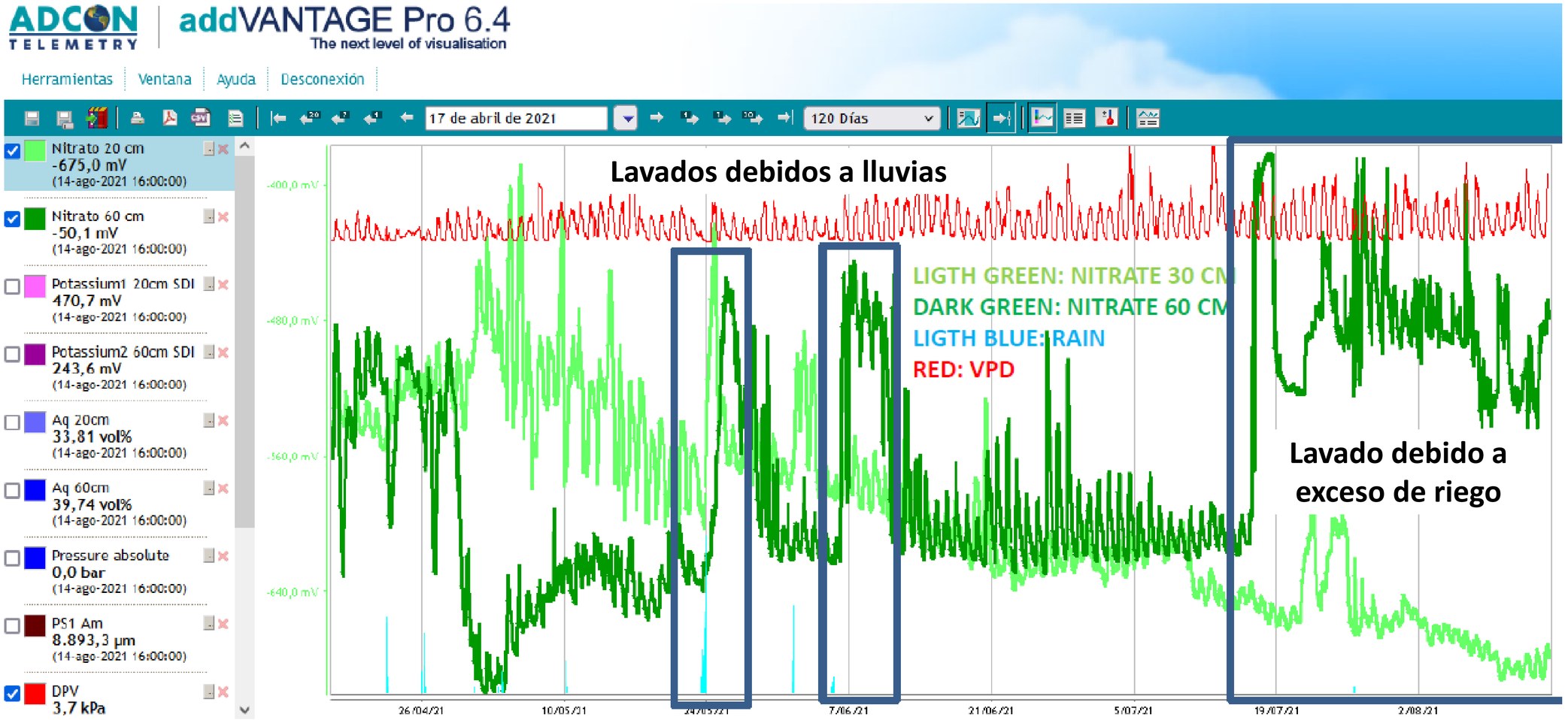
NUTRISENS

Measures the nitrate and potassium concentration in the soil under the dripper

POTASSIUM



NITRATE



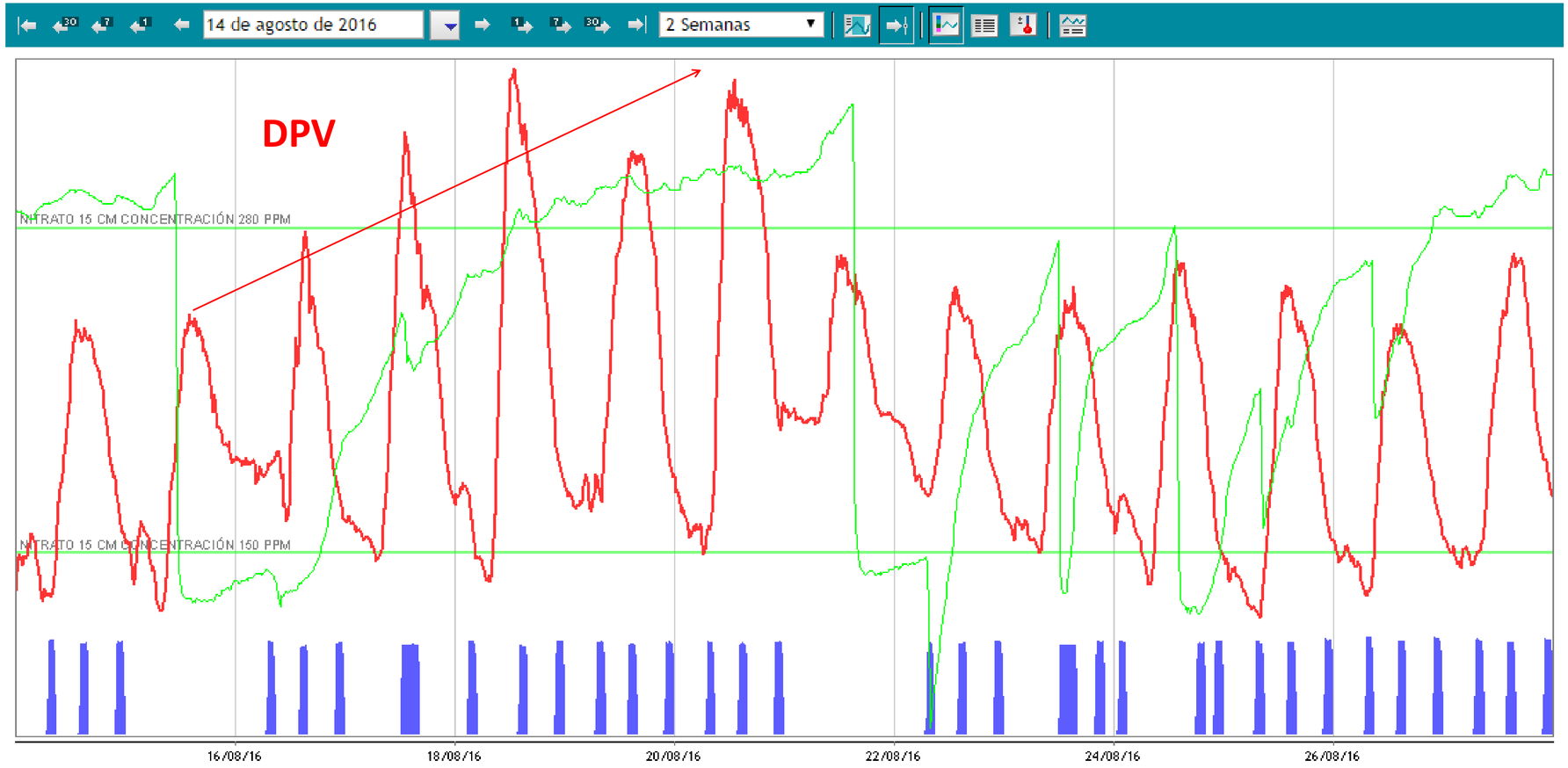
NITRATO 30 CM

NITRATO 60 CM

verde smart co.

Estrés por ↑DPV

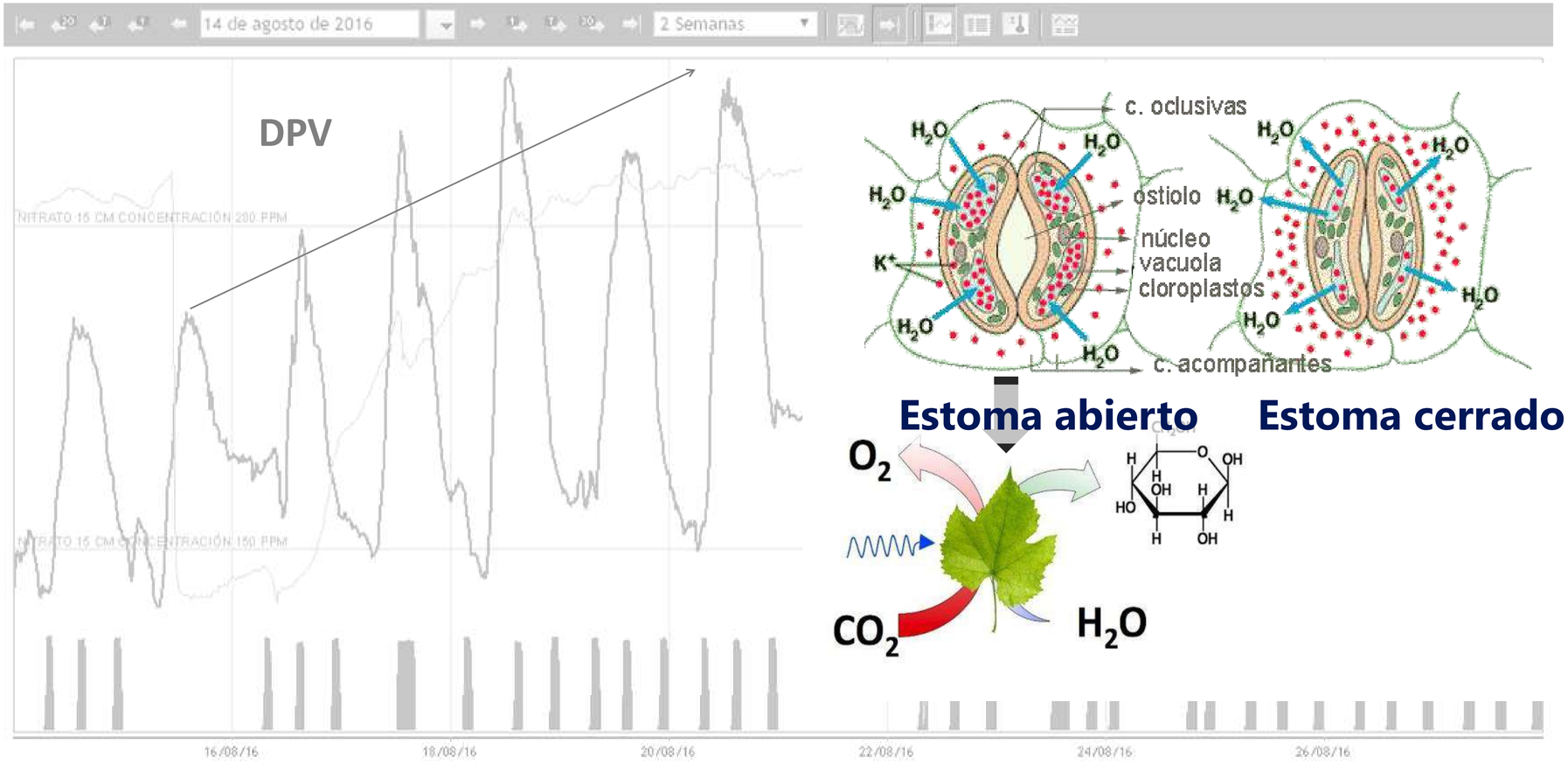
Podemos entender la influencia del estrés climático en la absorción del nitrato



ACUMULACIÓN DE NITRATO EN RAICES (VERDE) CUANDO AUMENTA EL DPV,

Estrés por ↑DPV

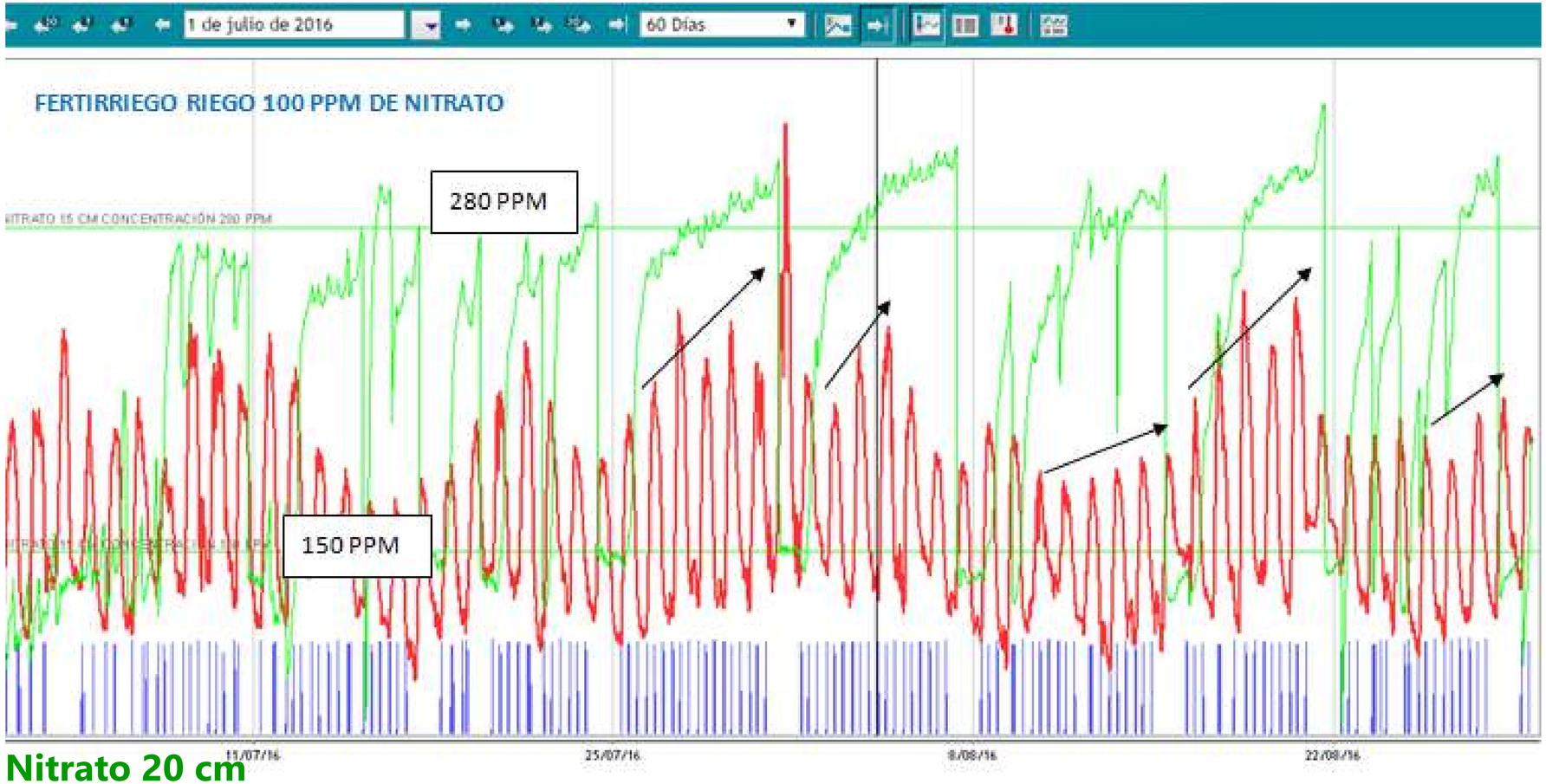
Podemos entender la influencia del estrés climático en la absorción del nitrato



↑ DPV → cierre estomas → ↓ actividad fotosintética → ↓ consumo NO_3^-

Estrés por ↑DPV

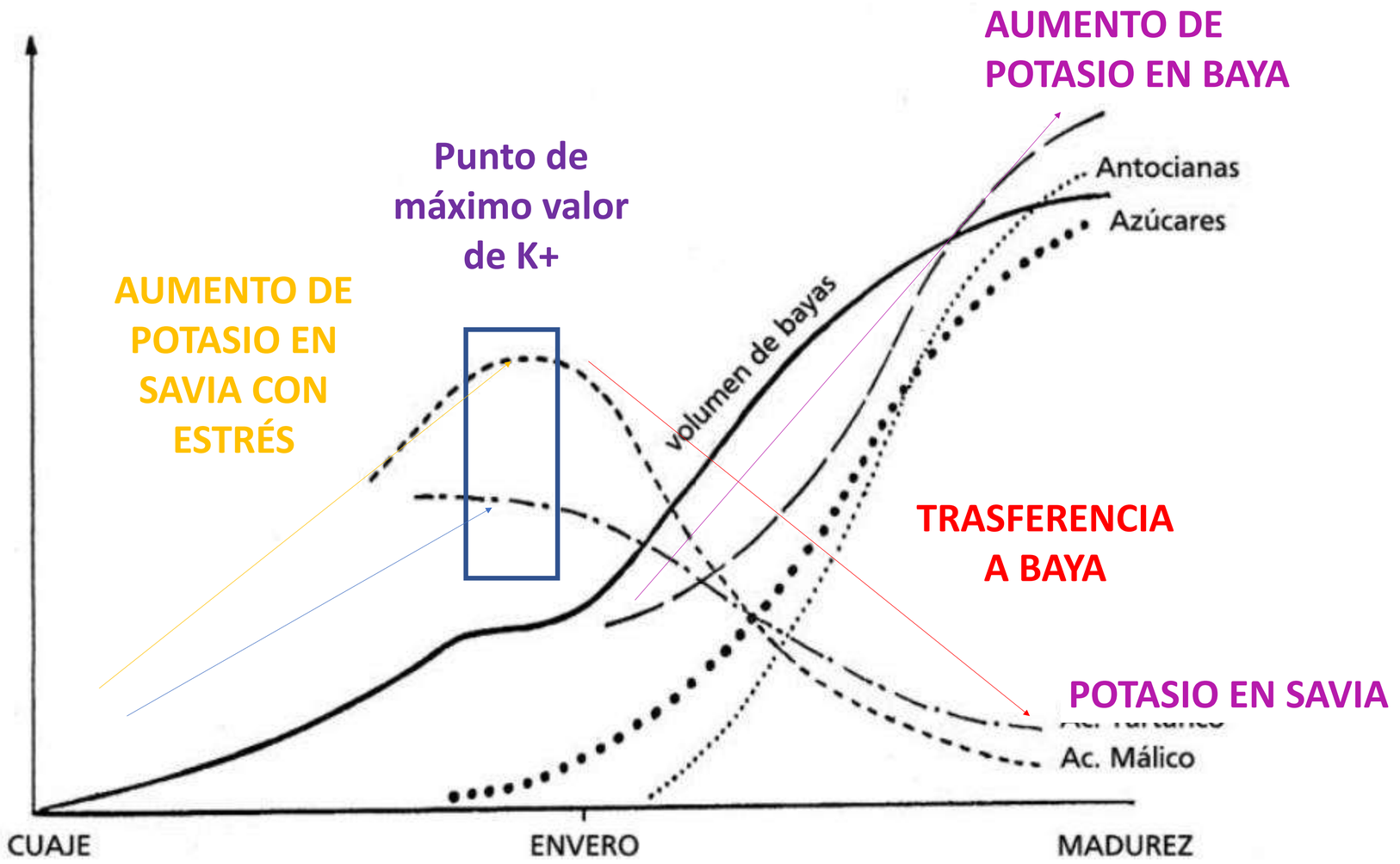
Ejemplo mandarina: acumulación de nitratos por altos DPV sin cambiar el riego



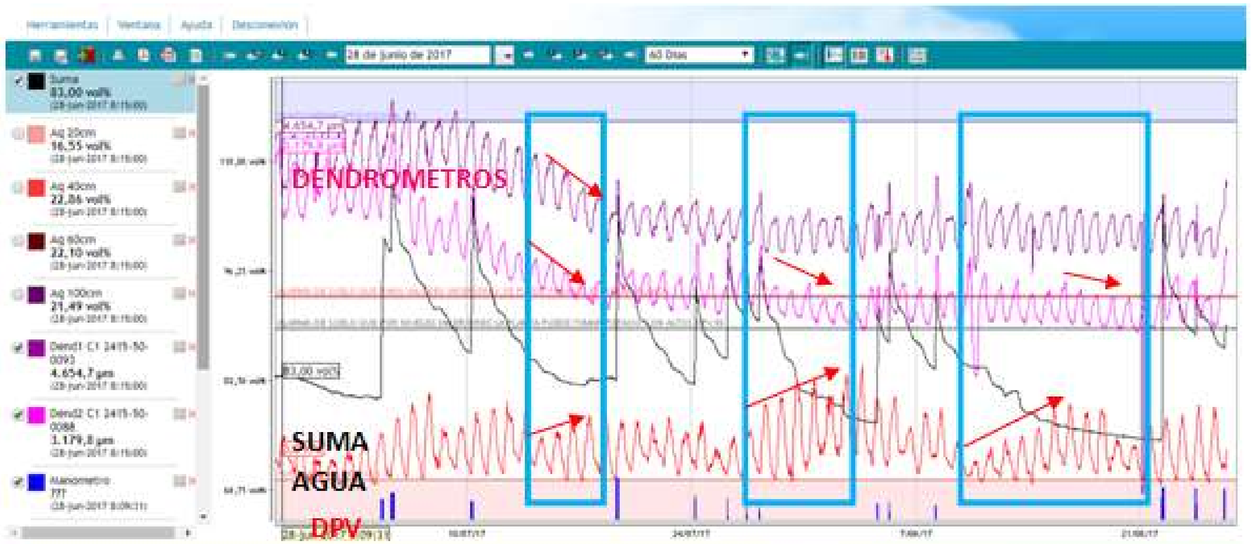
Nitrato 20 cm

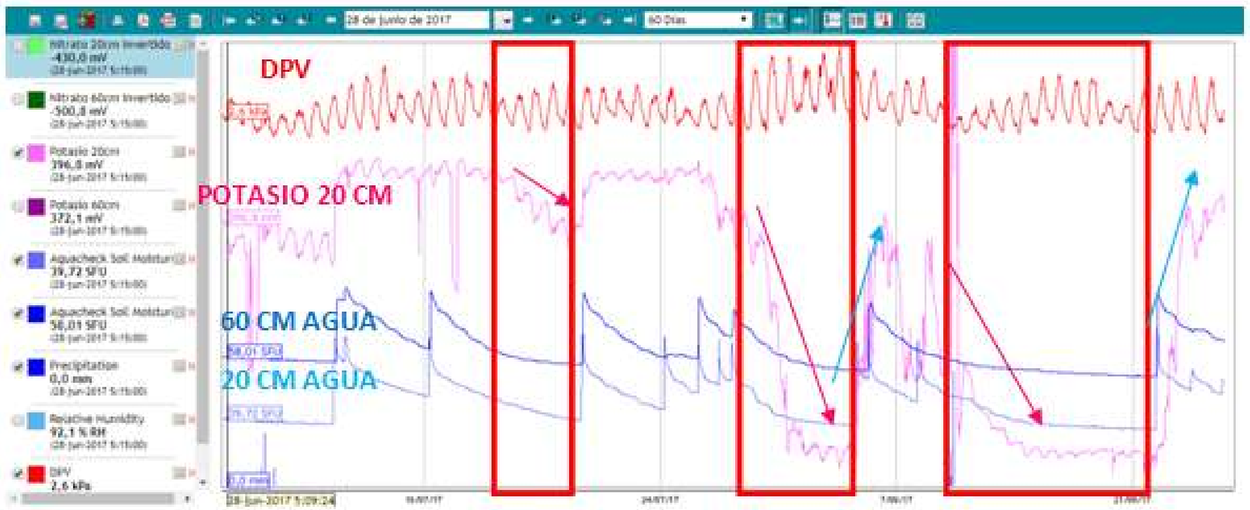
ACUMULACIÓN DE NITRATO EN RAICES (VERDE) CUANDO AUMENTA EL DPV,

CURVA DE EVOLUCIÓN DE POTASIO EN SAVIA Y EN BAYA



POTASIO EN VIÑA: LA PLANTA TOMA POTASIO AL TENER ESTRÉS CLIMATICO E HIDRICO Y DEJA DE TOMARLO AL REGAR





POTASIO EN VIÑA: LA PLANTA TOMA POTASIO AL TENER ESTRÉS CLIMATICO E HIDRICO





Caso de los sensores de potasio de 20 cm y 40 cm en donde se observa cómo disminuyen en la gráfica porque aumenta su consumo.



Thanks to my research team and you all for your attention

e-mail:
a.diaz@csic.es

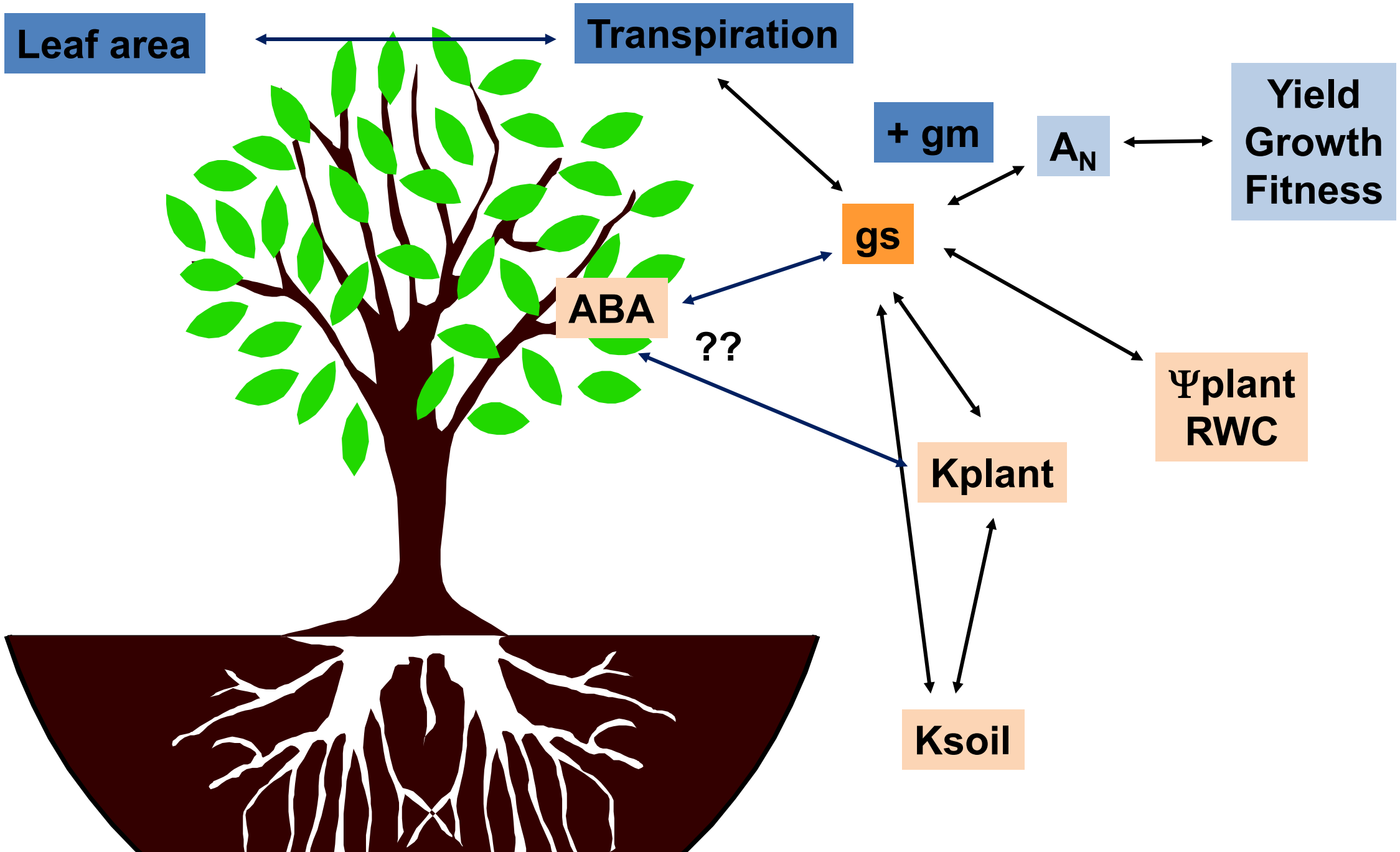
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IRNAS

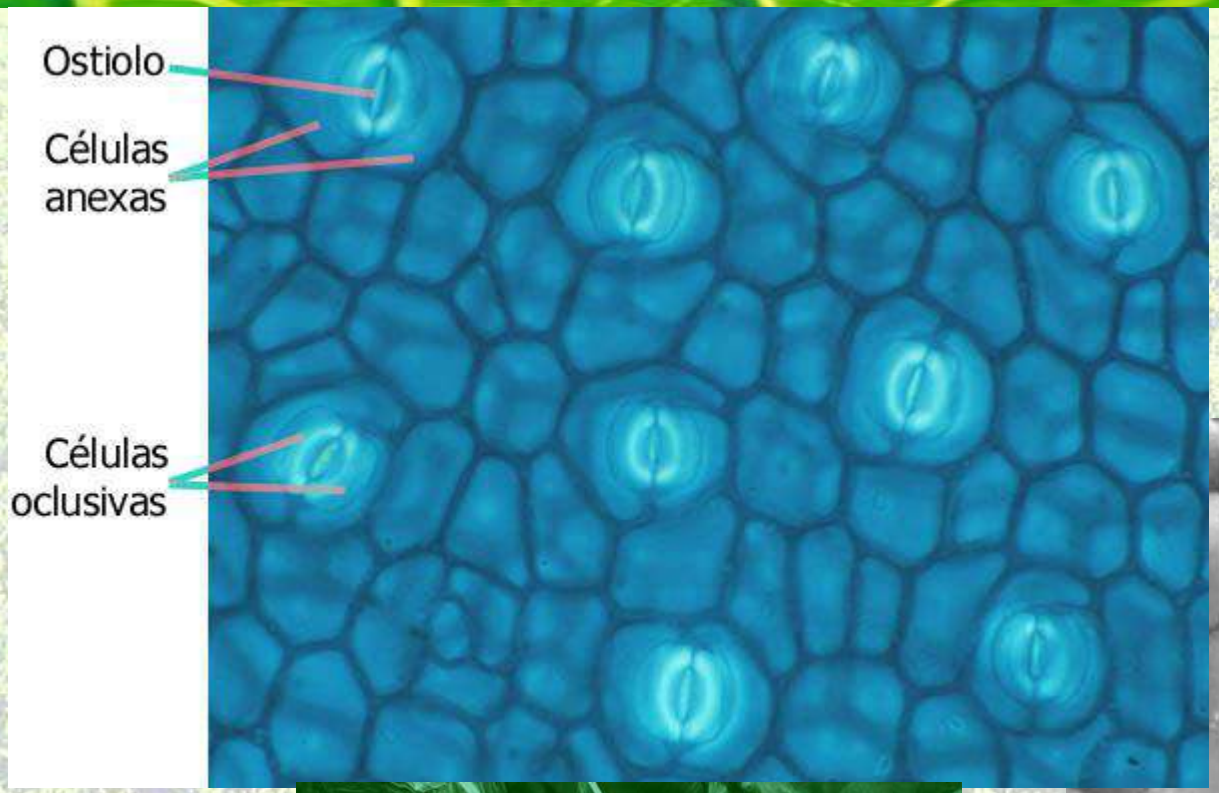


Leaf gas exchange and energy balance

Antonio Díaz Espejo

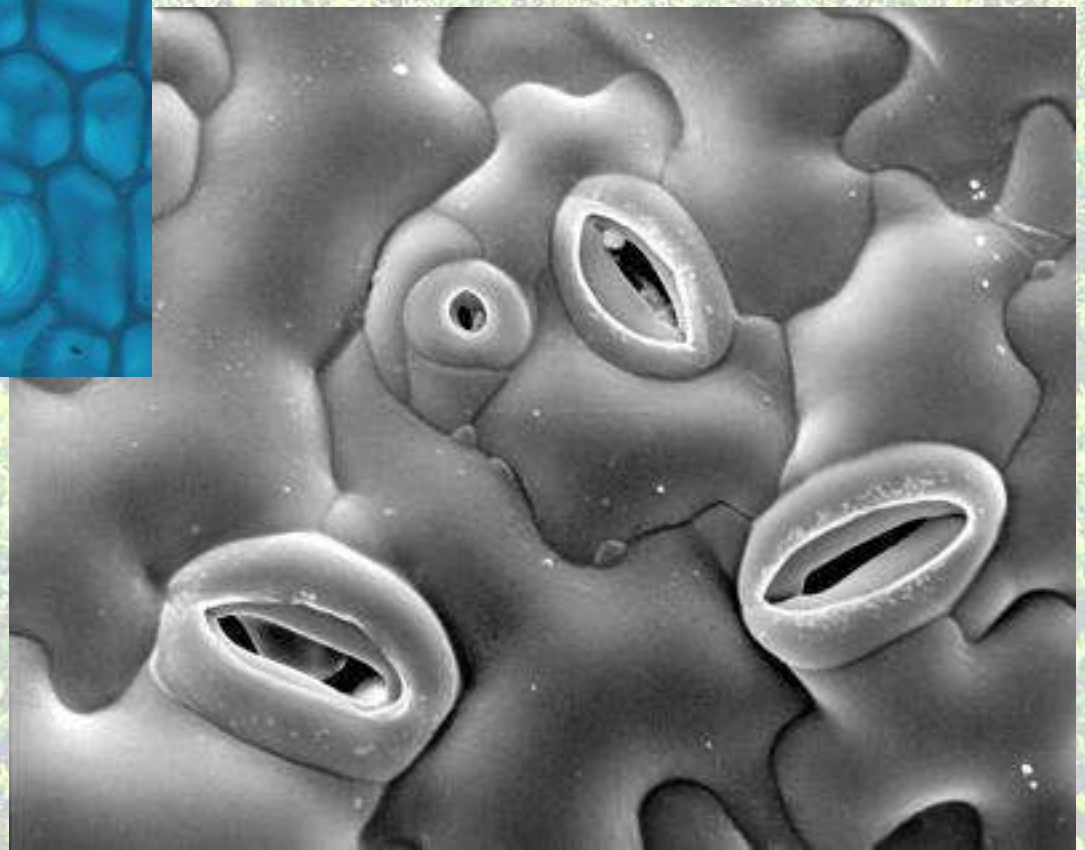

Leaf area
Transpiration
+ gm
A_N
Yield
Growth
Fitness
gs
ABA
??
Ψplant
RWC
Kplant
Ksoil

Stomata









Stomatal mechanics



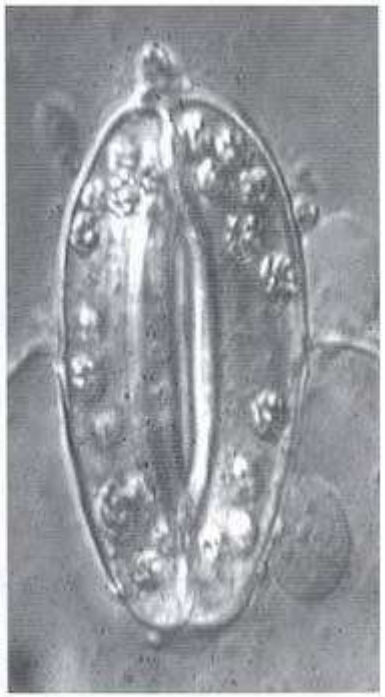
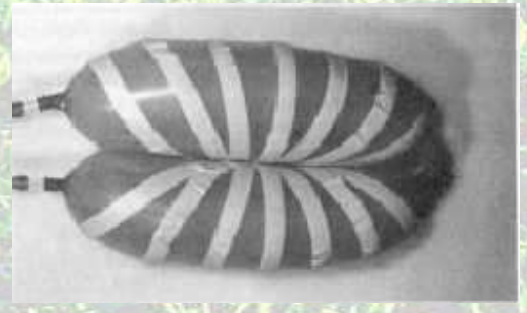
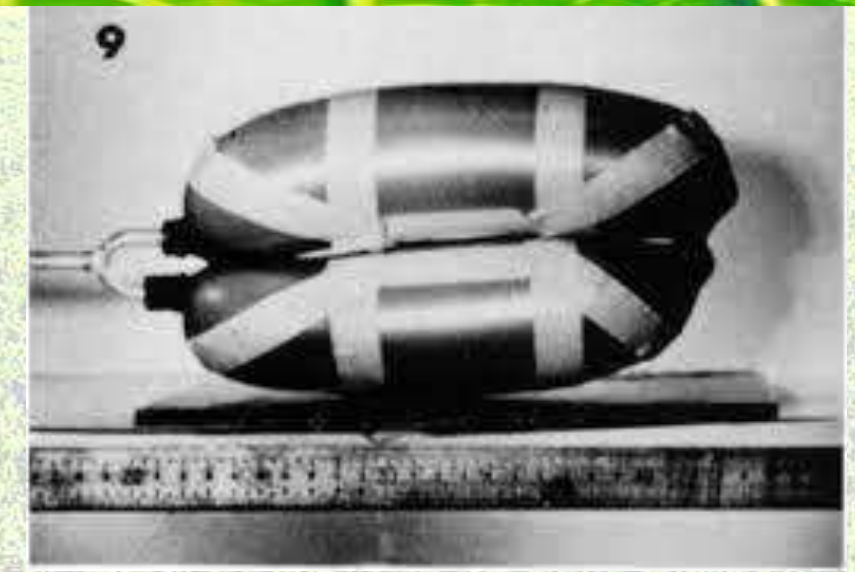


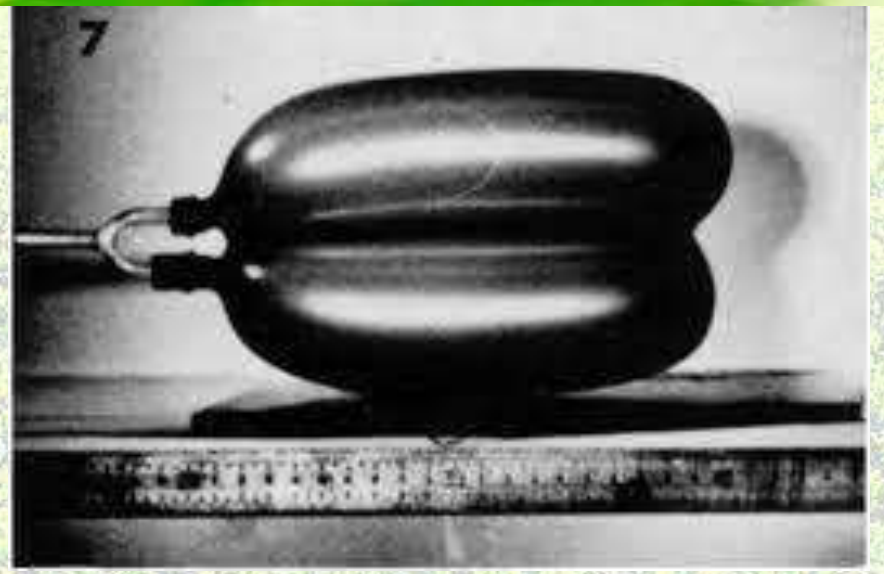
Image reproduced from Plant Physiology, Eds: L. Taiz and E. Zeiger, 2nd edition, Sinauer Associates, Inc. Publisher, Sunderland MA, USA. p. 523





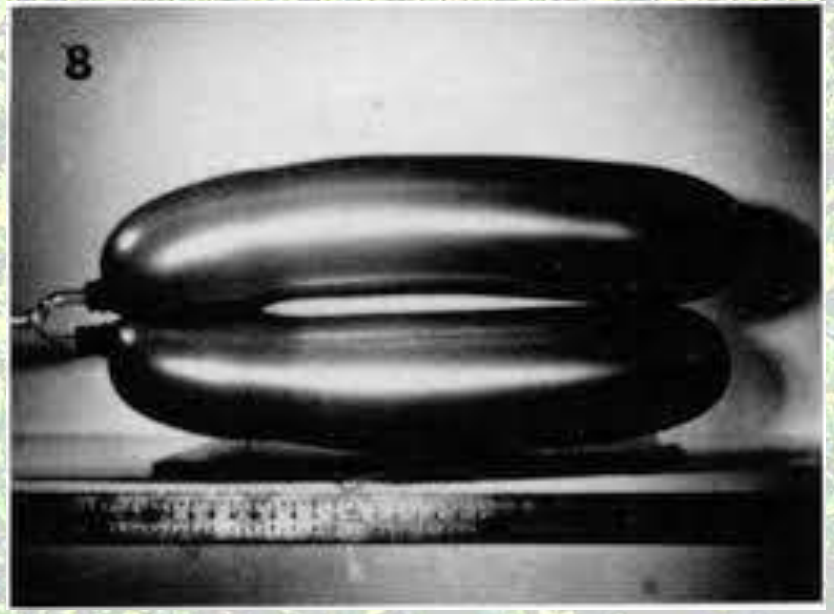
Stomatal mechanics



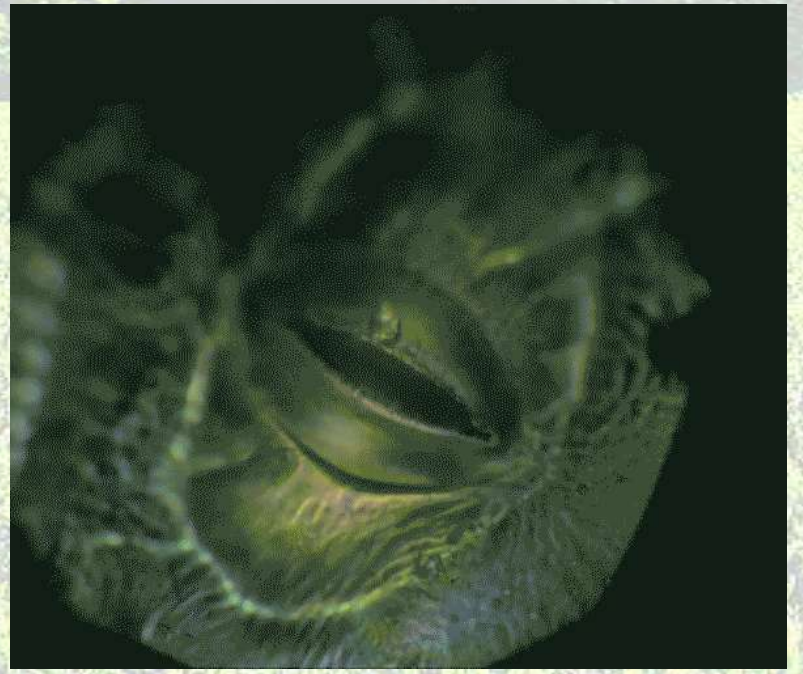


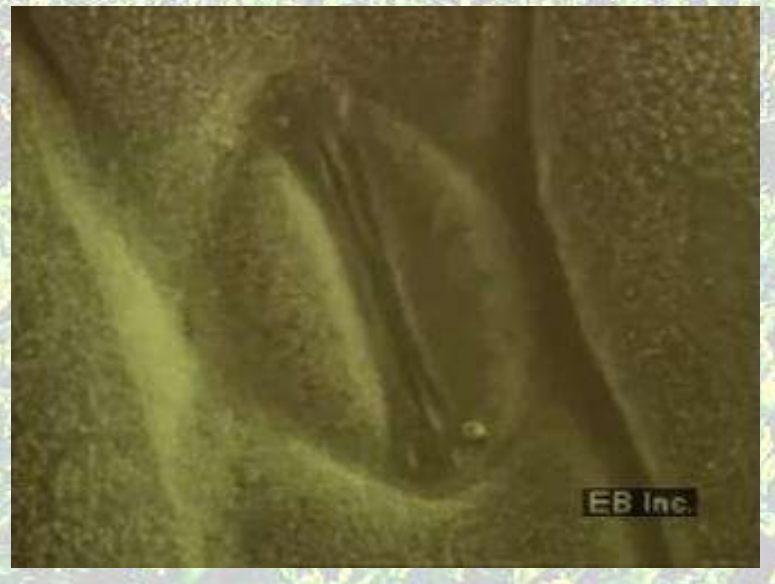


Turgor

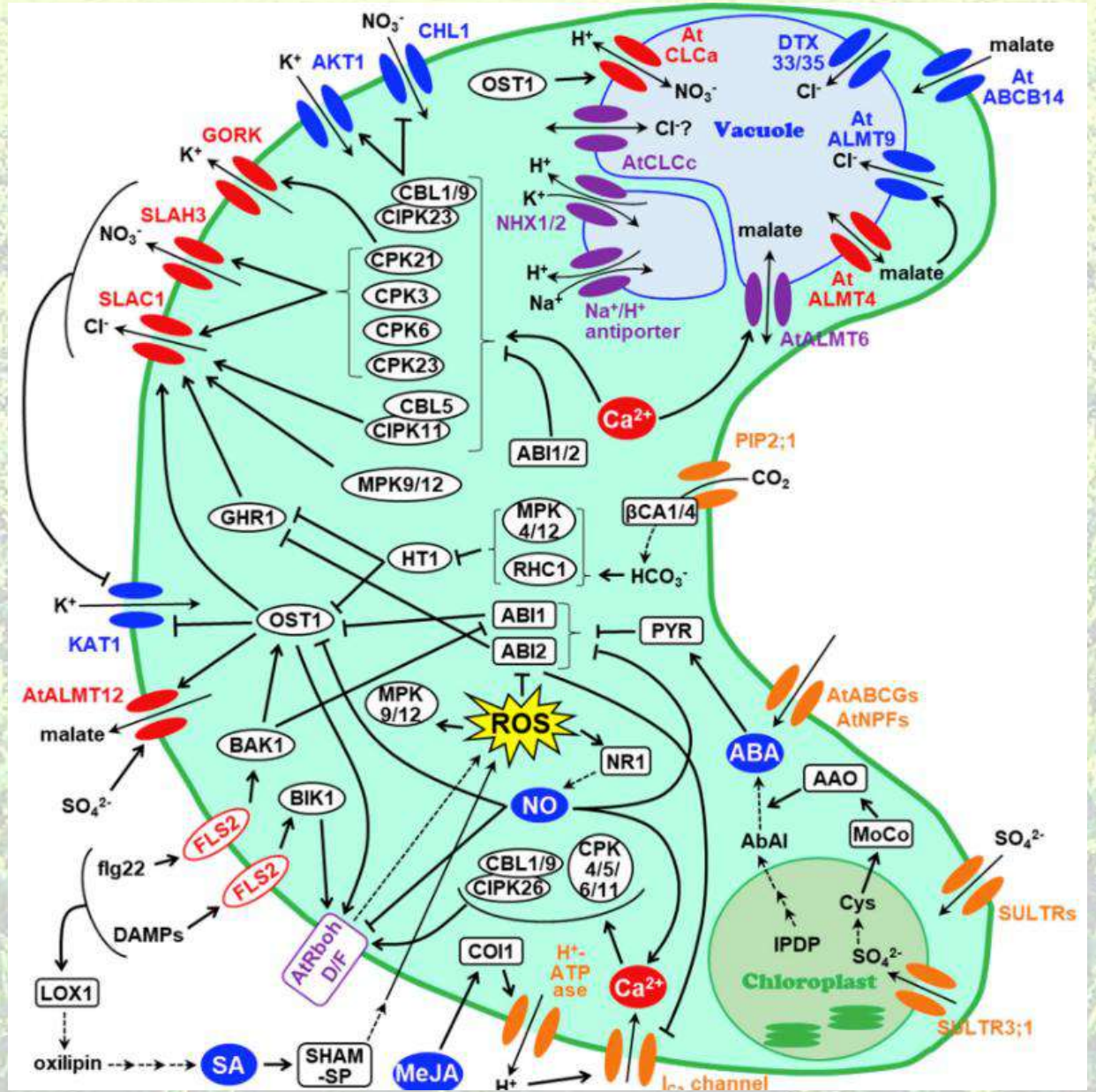






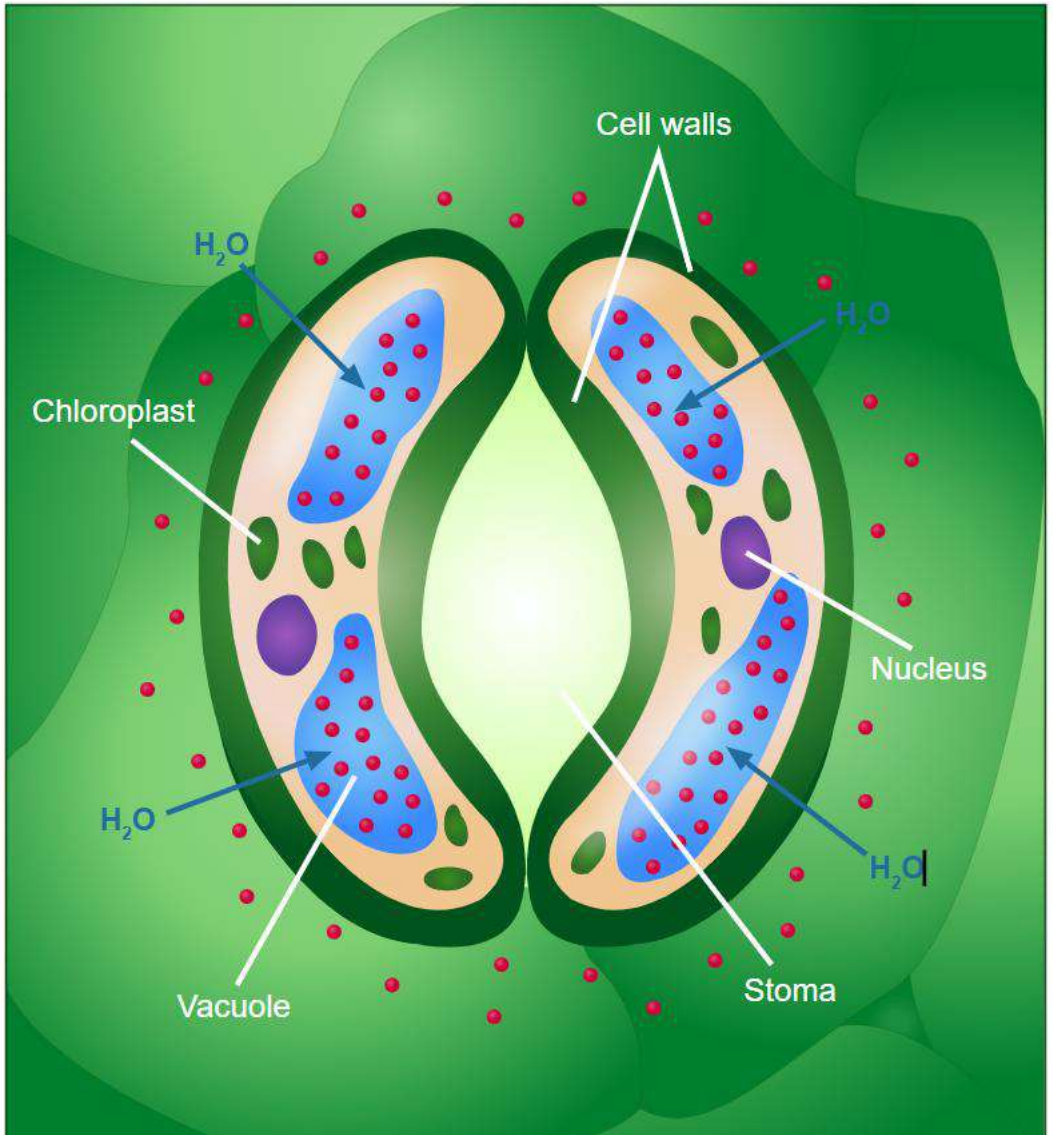

EB Inc.

Stomatal conductance regulation

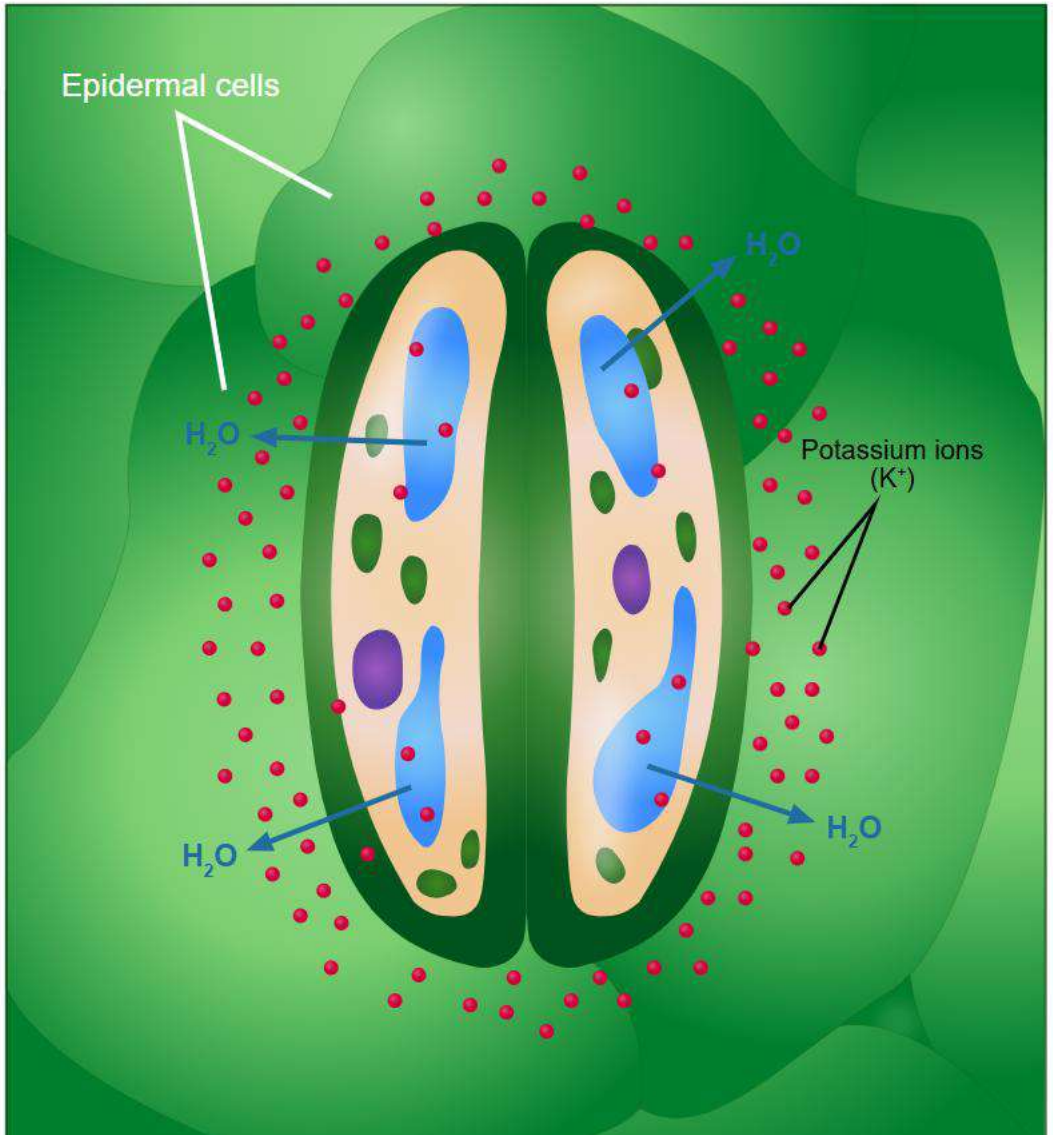


Moving ions

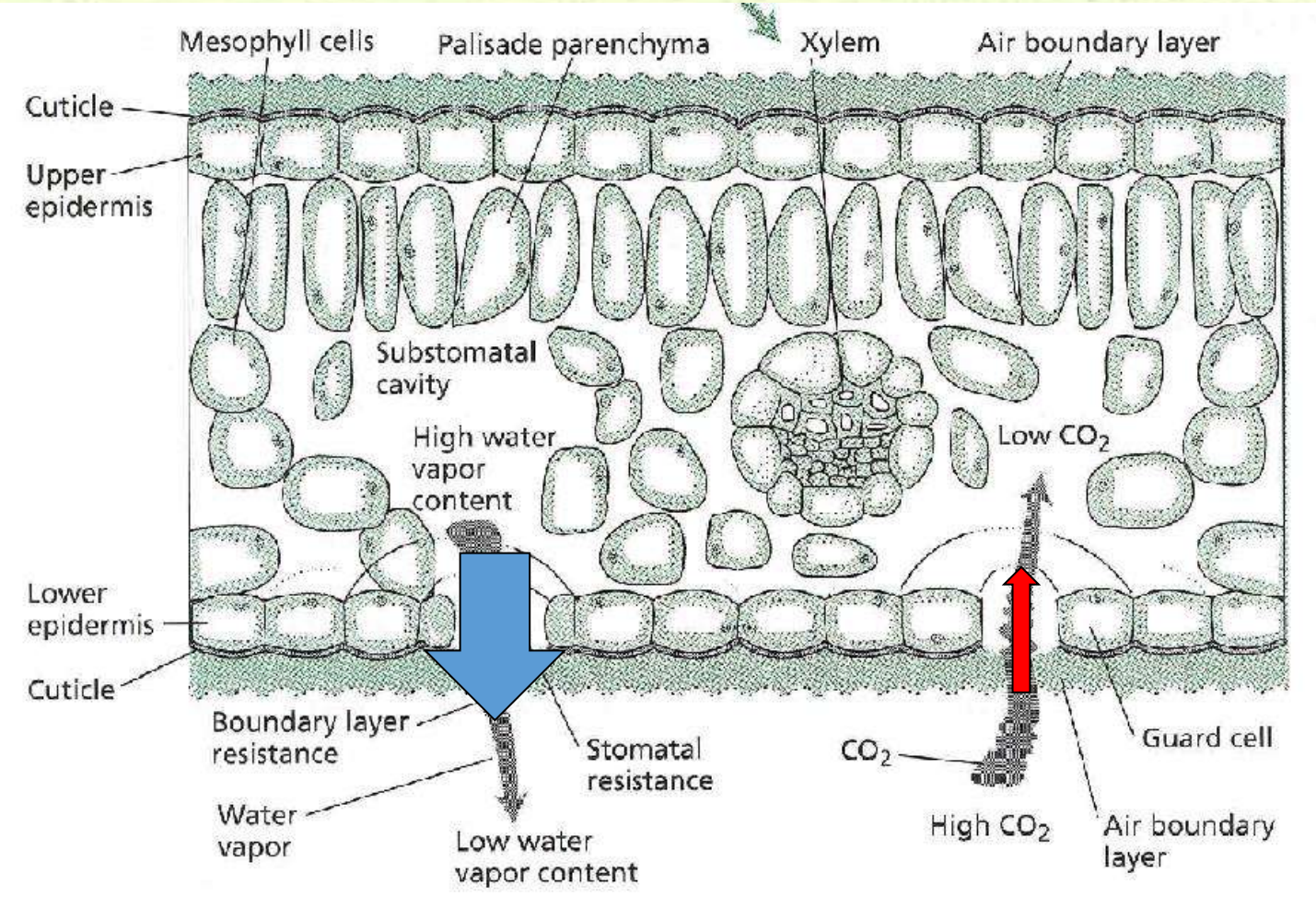
Guard cells (swollen)



Guard cells (shrunken)

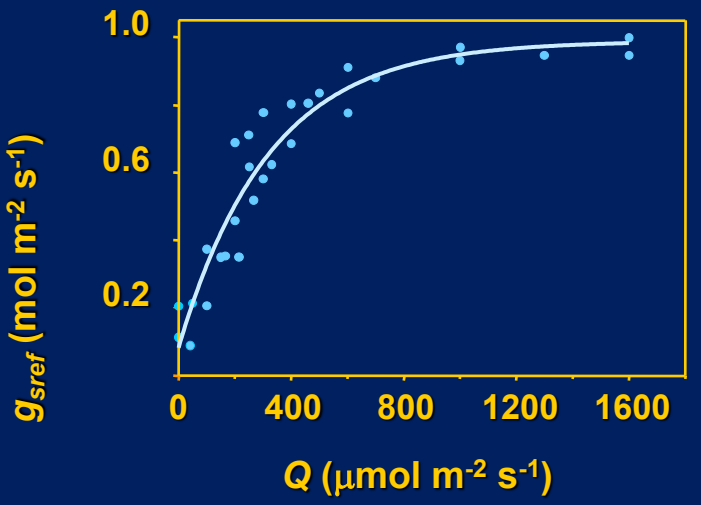


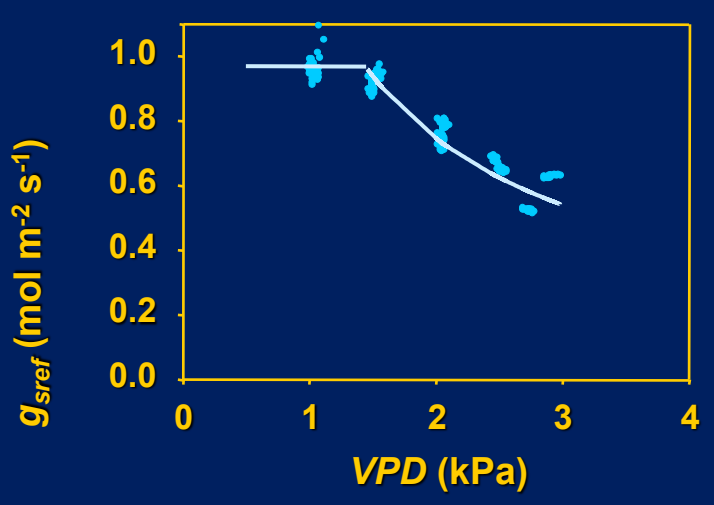
Leaf gas exchange

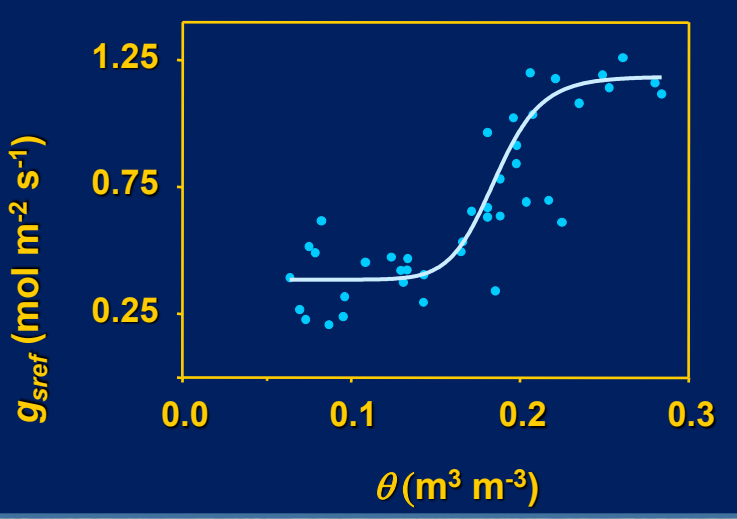


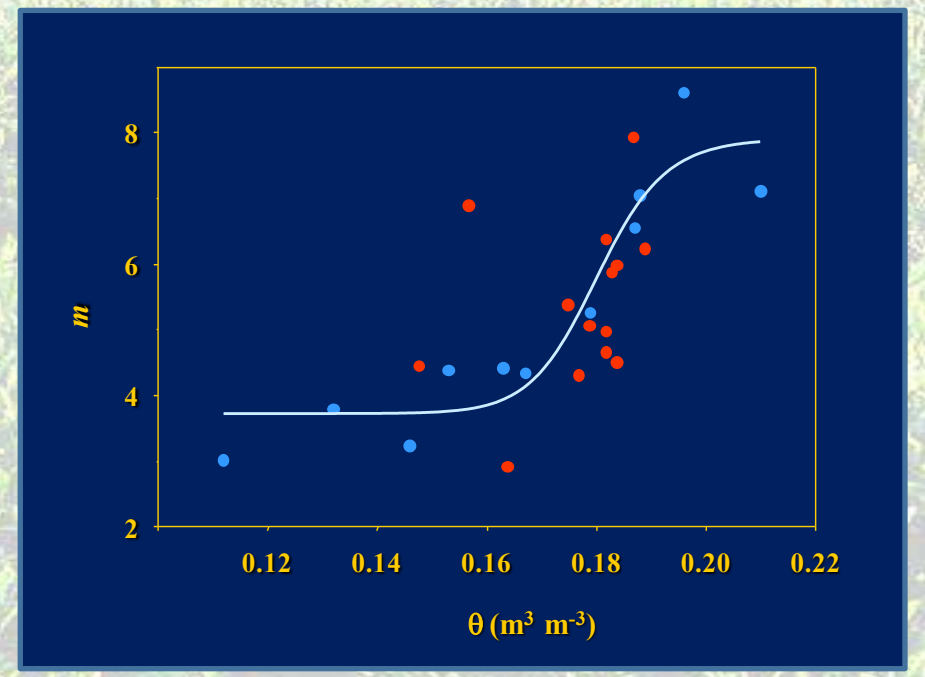
H_2O 300:1 CO_2

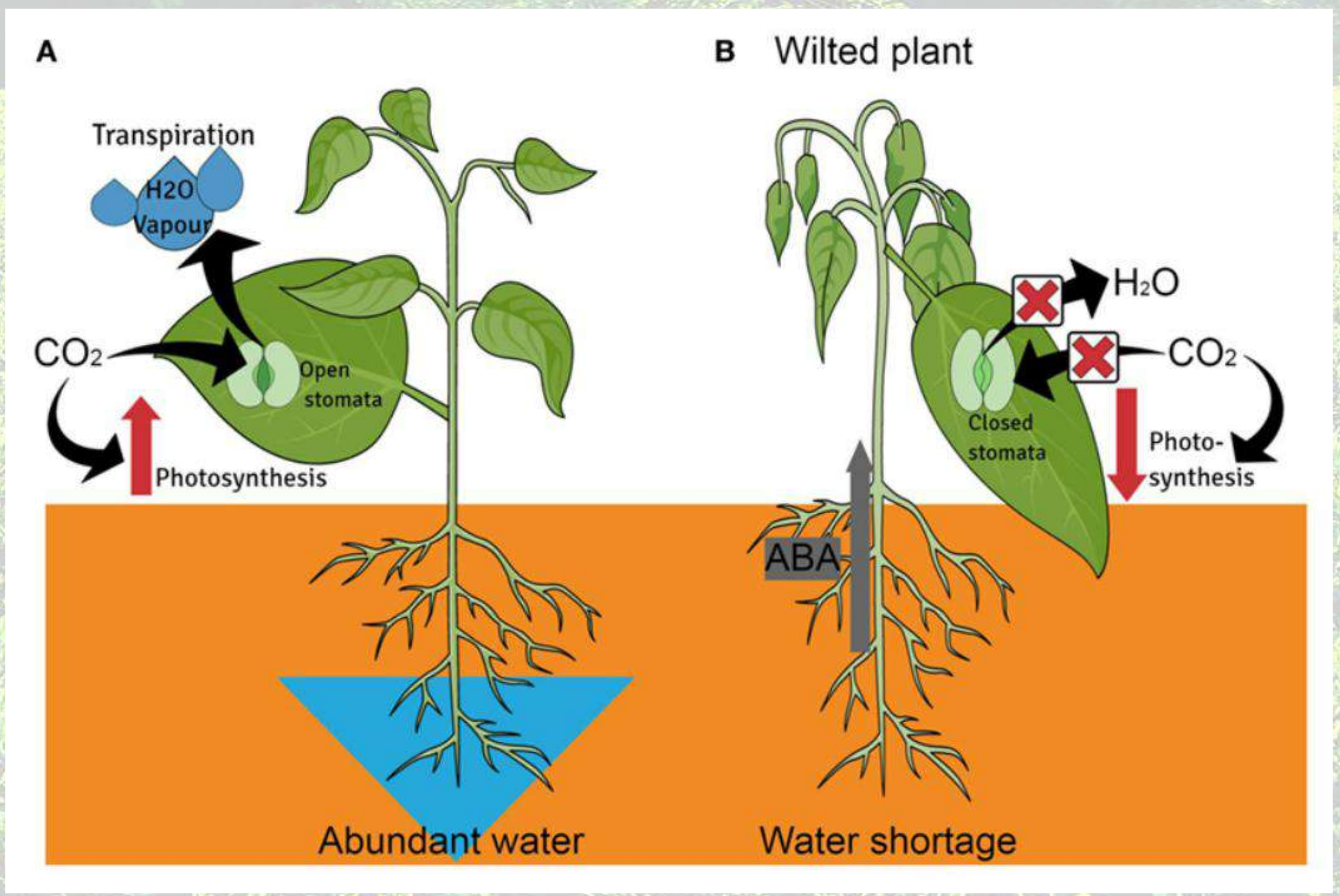
In the process of carbon fixation → 6:1


1.0
0.6
0.2
g_{sref} (mol m^{-2} s^{-1})
0
400
800
1200
1600
Q (μmol m^{-2} s^{-1})

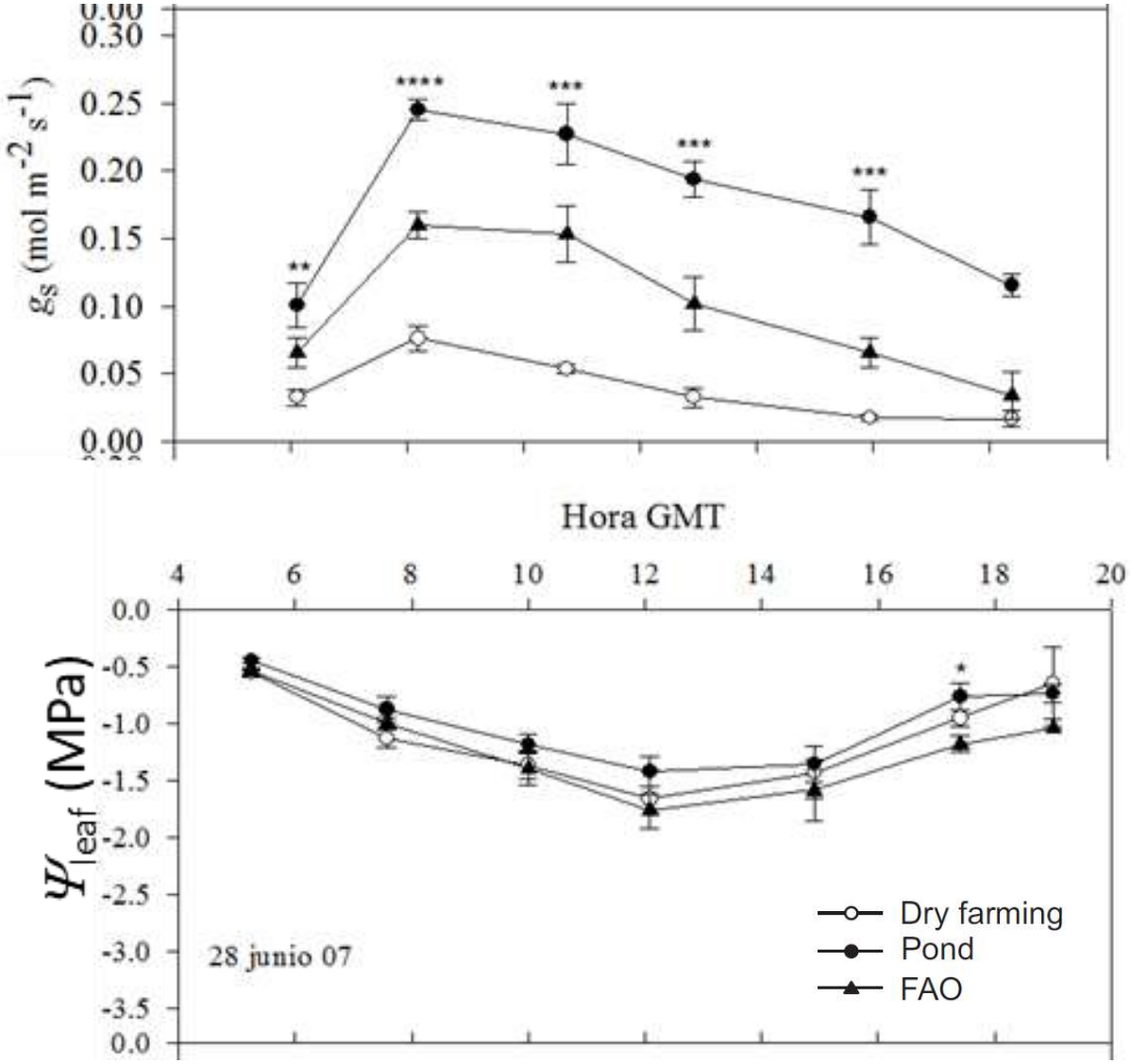

1.0
0.8
0.6
0.4
0.2
0.0
g_{sref} (mol m^{-2} s^{-1})
0
1
2
3
4
VPD (kPa)


1.25
0.75
0.25
g_{sref} (mol m^{-2} s^{-1})
0.0
0.1
0.2
0.3
θ (m^3 m^{-3})

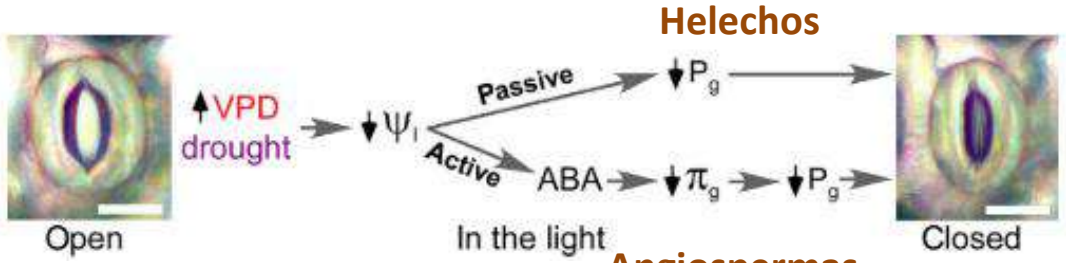

8
6
4
2
m
0.12
0.14
0.16
0.18
0.20
0.22
θ (m^3 m^{-3})


A
Transpiration
H2O
Vapour
CO2
Open
stomata
Photosynthesis
Abundant water
B
Wilted plant
H2O
CO2
Closed
stomata
Photo-
synthesis
ABA
Water shortage

Control of the risk of embolism

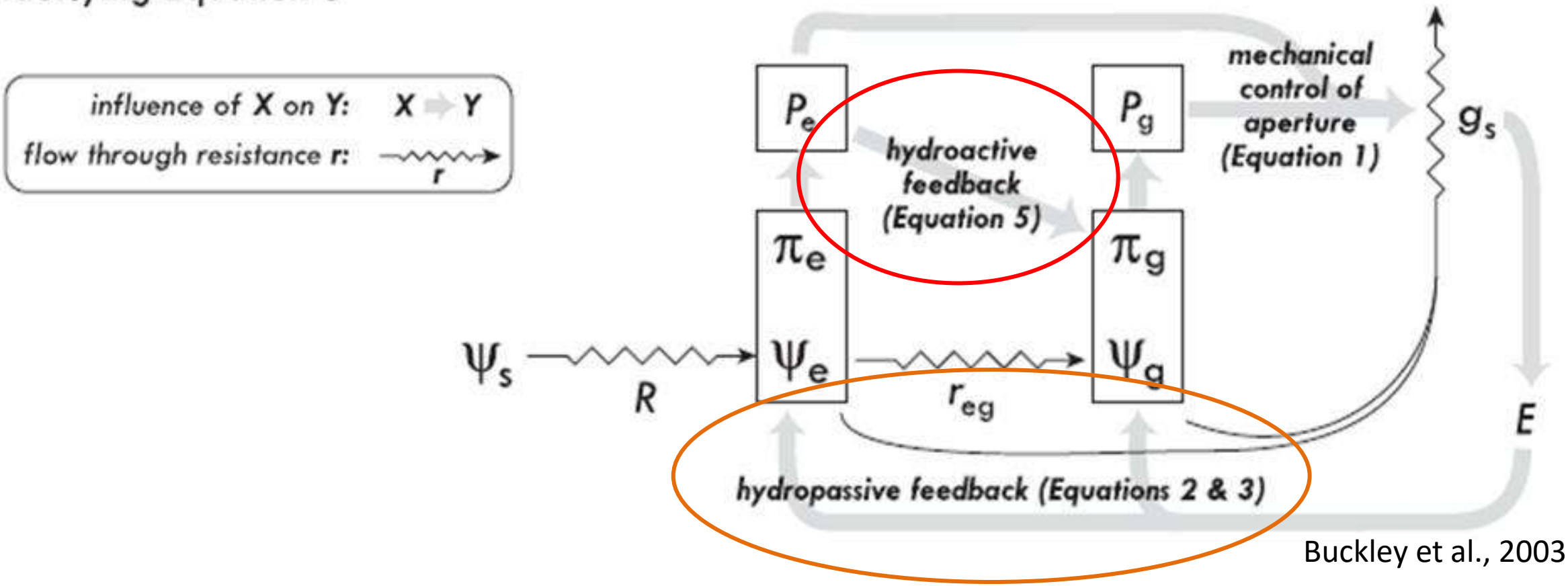


How is regulated the stomatal conductance?



Sussmilch et al 2017

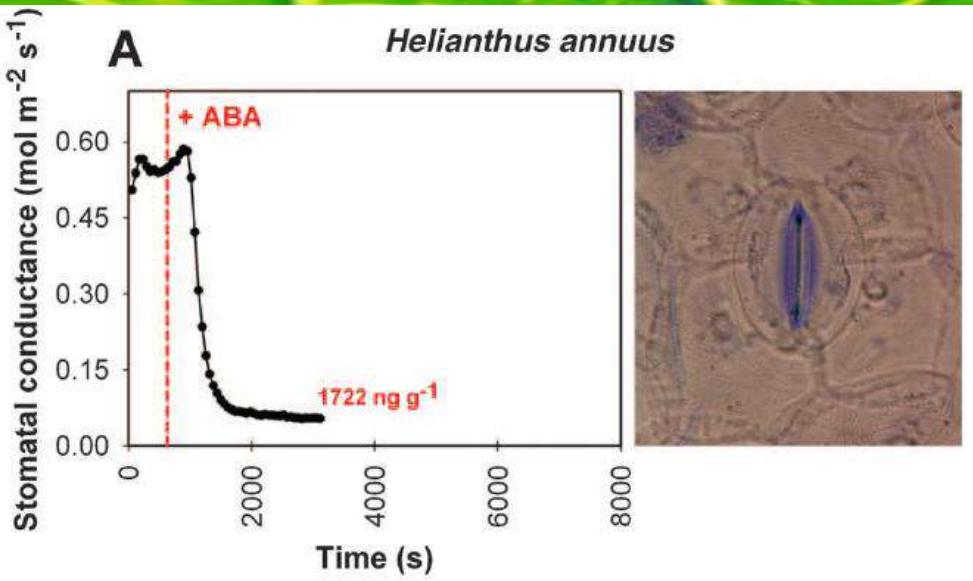
(c) flows and influences underlying Equation 6

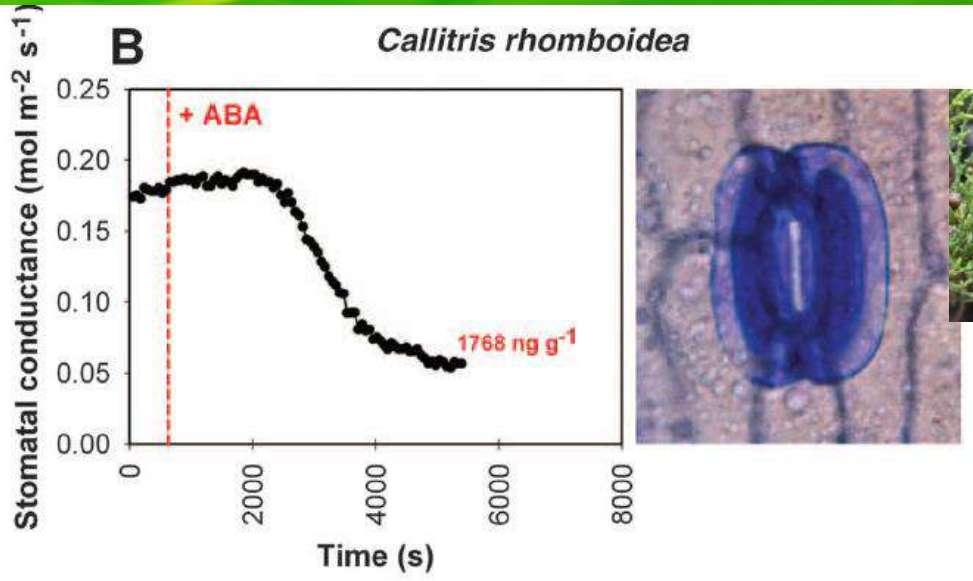


Buckley et al., 2003

The response of vascular plants

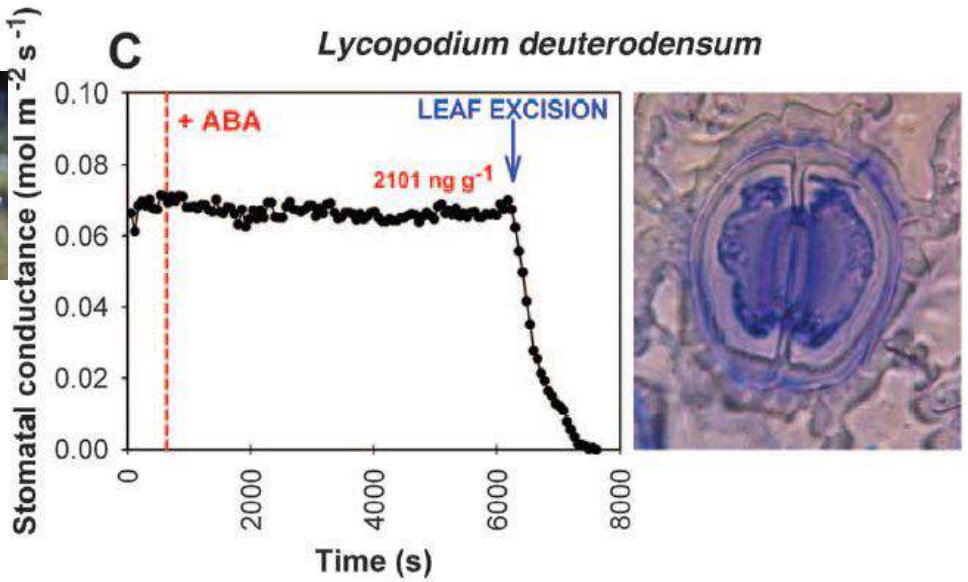


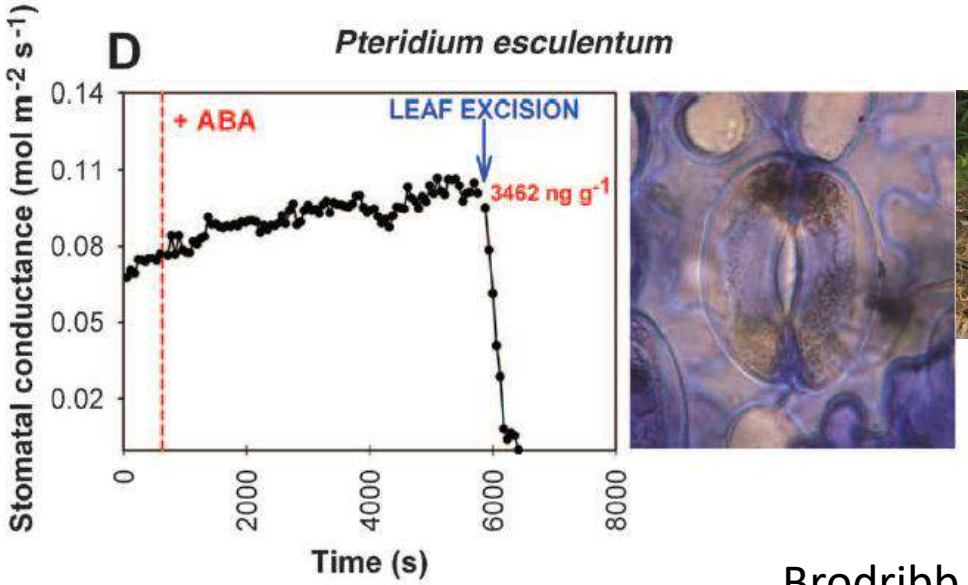








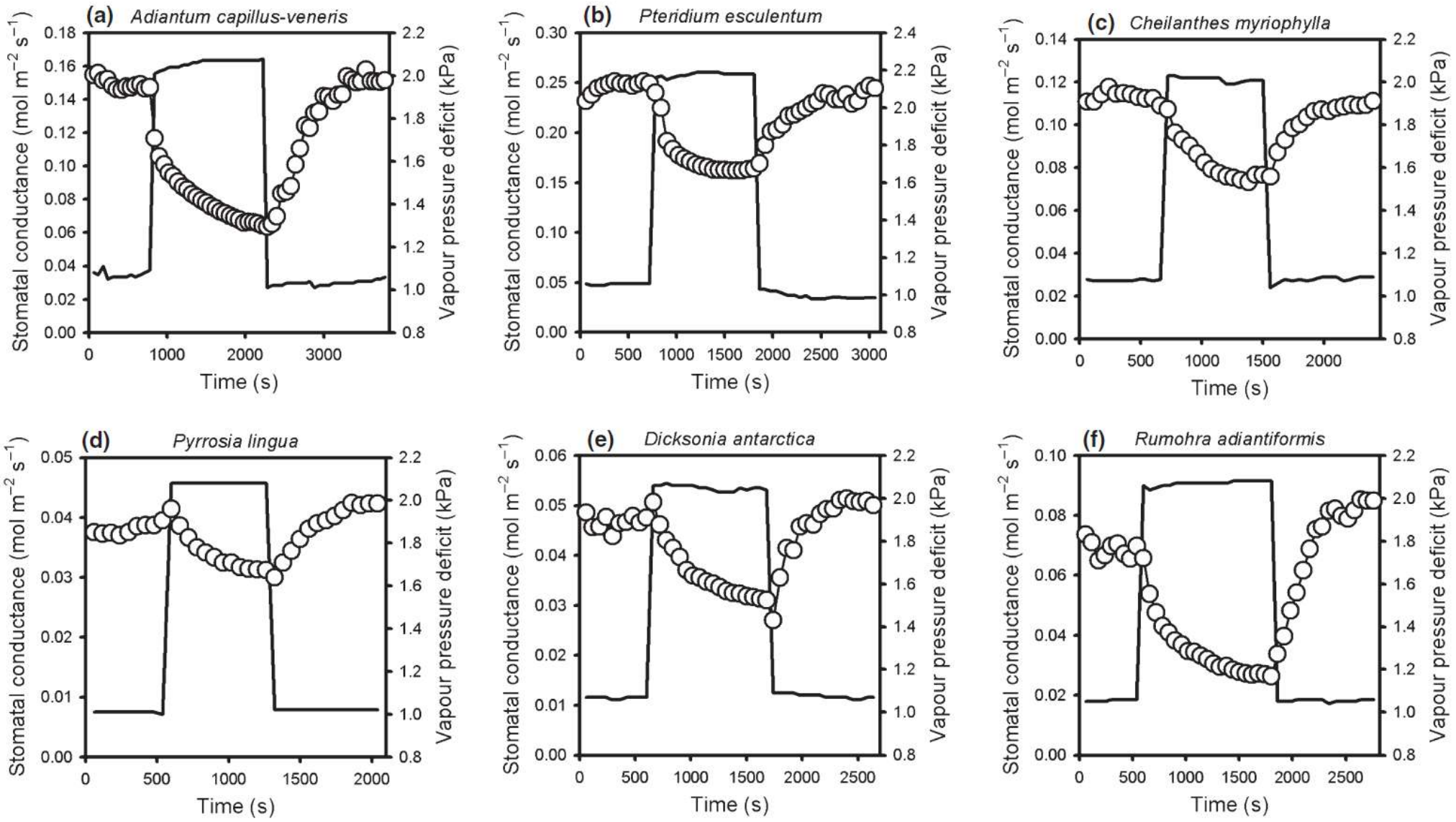






Brodribb et al., 2011

Some species are just hydropassive



McAdam & Brodribb, 2013

Pteridophytes



Gymnosperms



Angiosperms



Hydropassive mechanism

Response to ABA

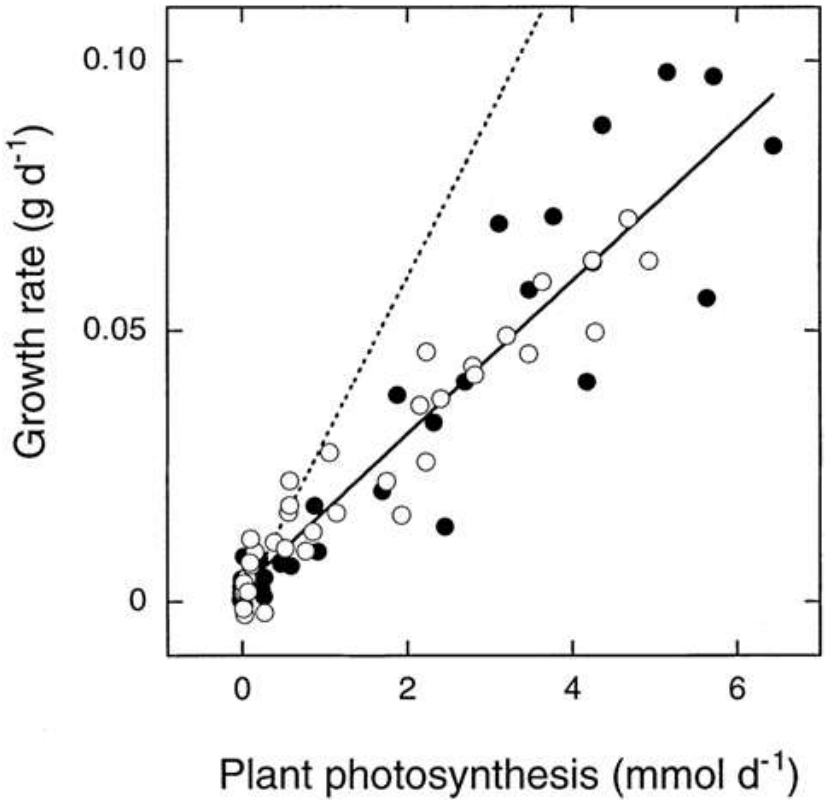
Hydroactive mechanism → ABA

Why was this hydroactive mechanism necessary?

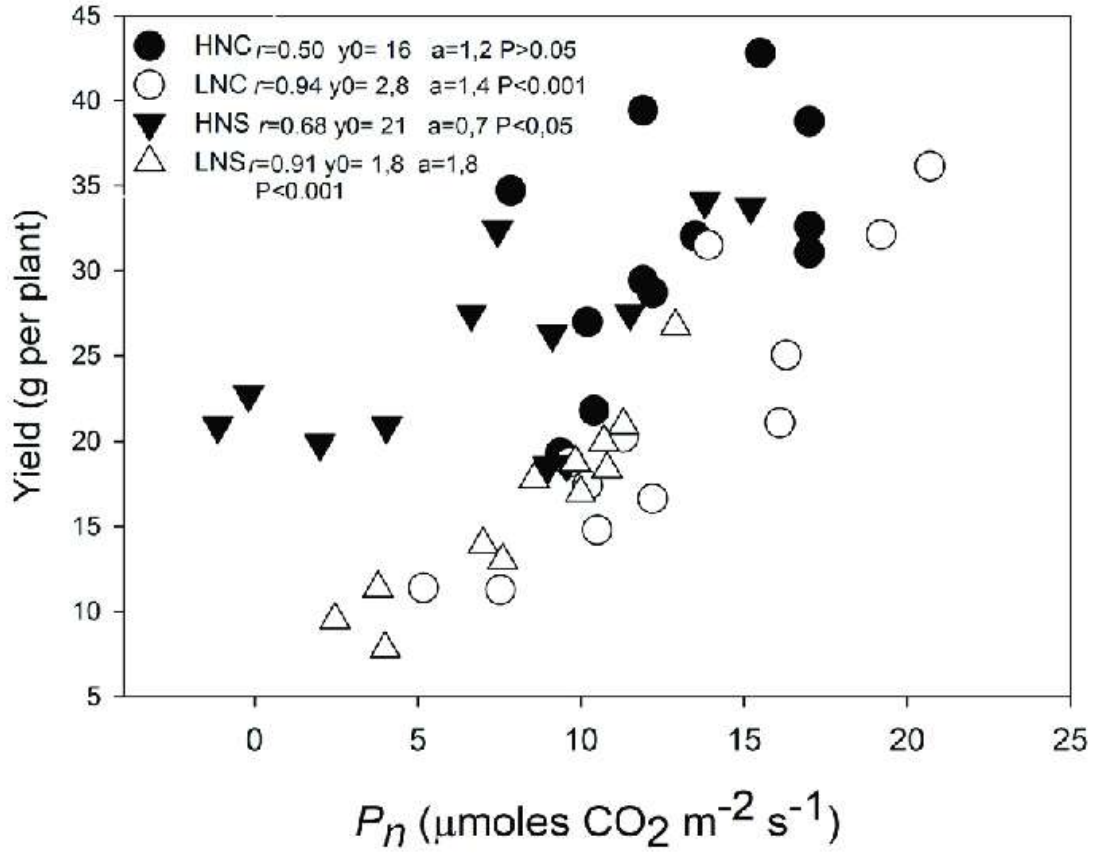
Hypothesis 1. Fast-growing or "unexpected" secondary effect

Hypothesis 2. Coordination of An-gs

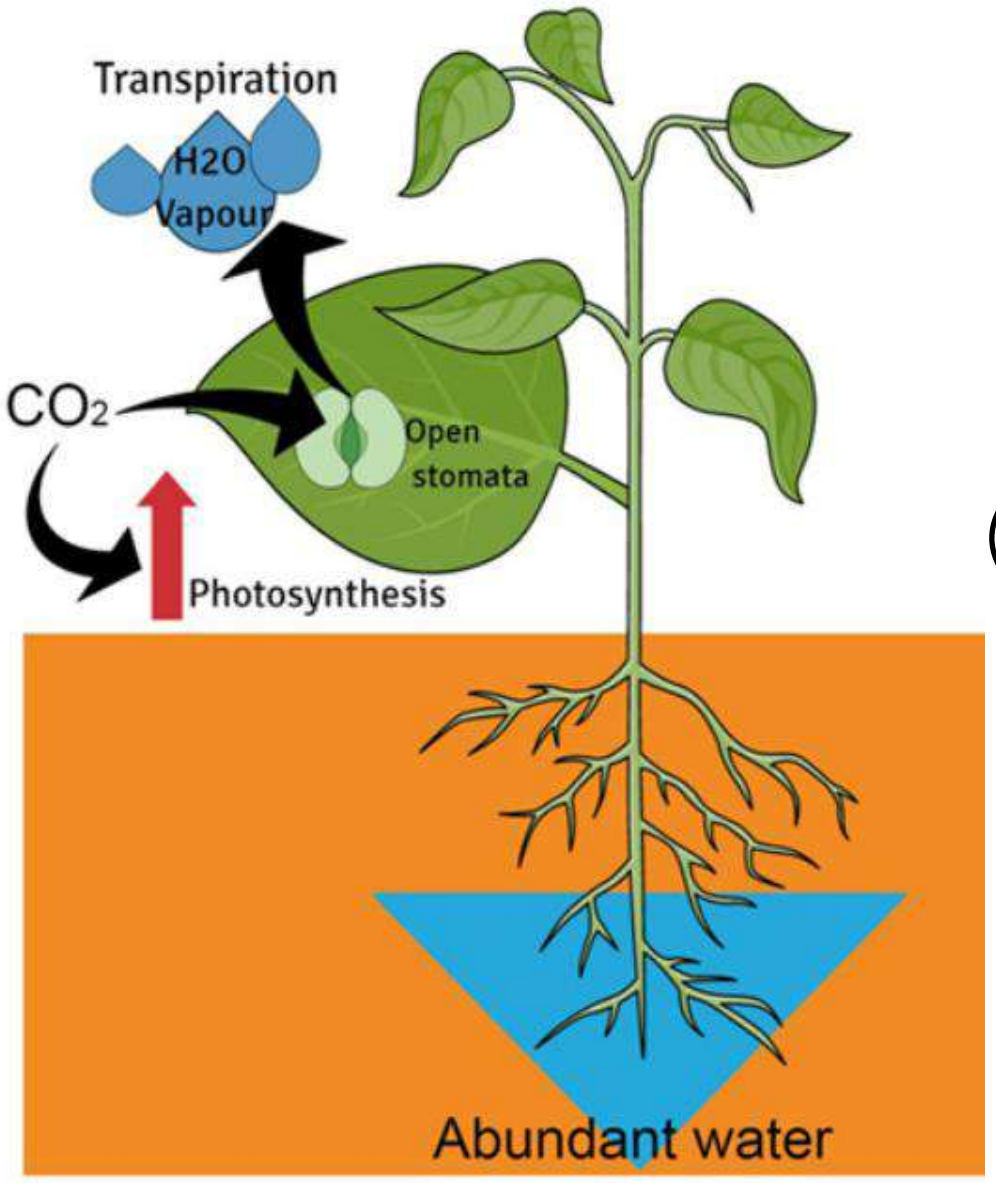
Photosynthesis and growth



Hikosaka et al., 1999



Bascuñan-Godoy et al., 2018



↑ Biomass, growth

↑ Photosynthesis

↑ Photosynthetic capacity

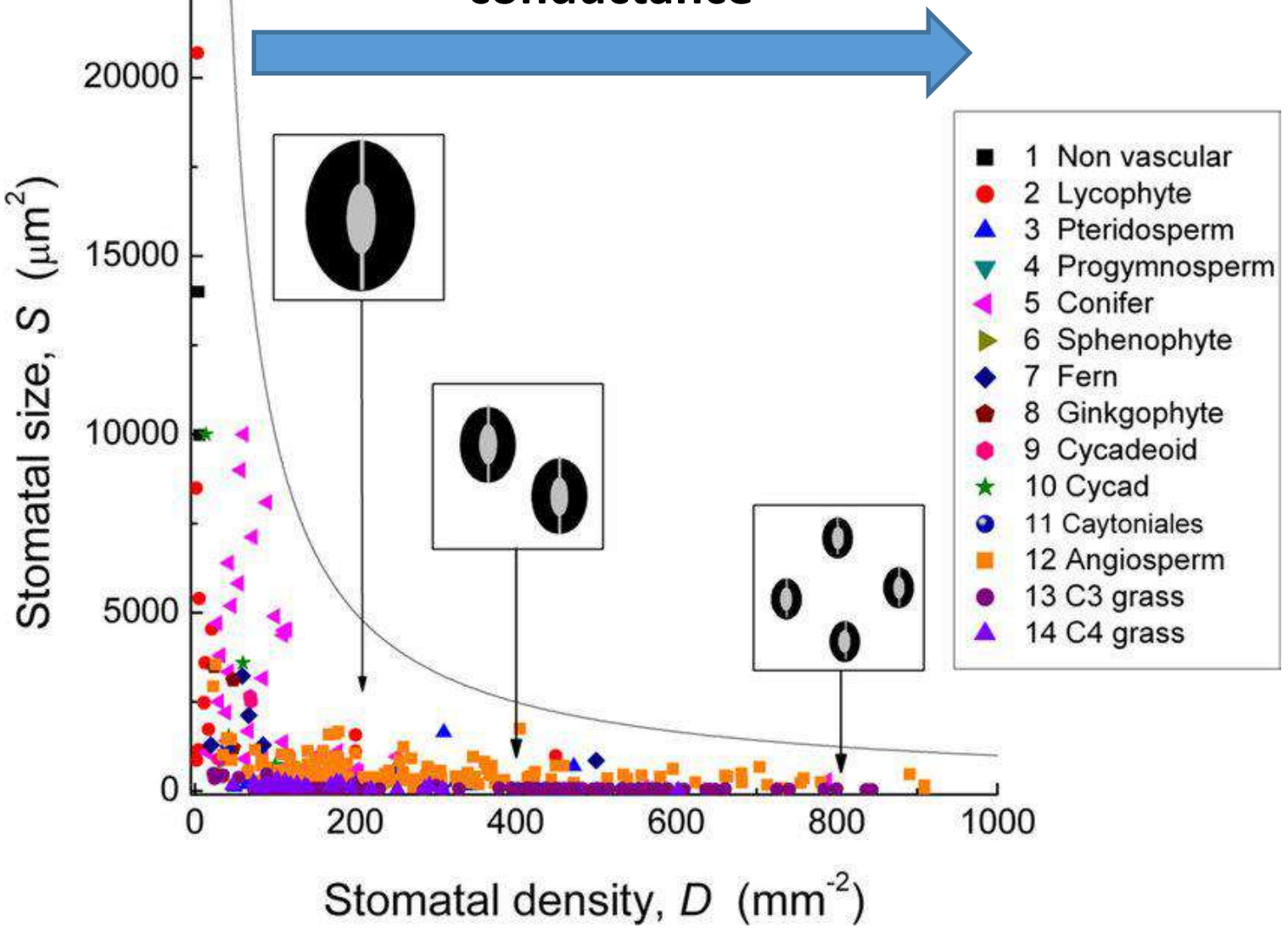
↑ CO_2 in the chloroplast

↑ stomatal conductance

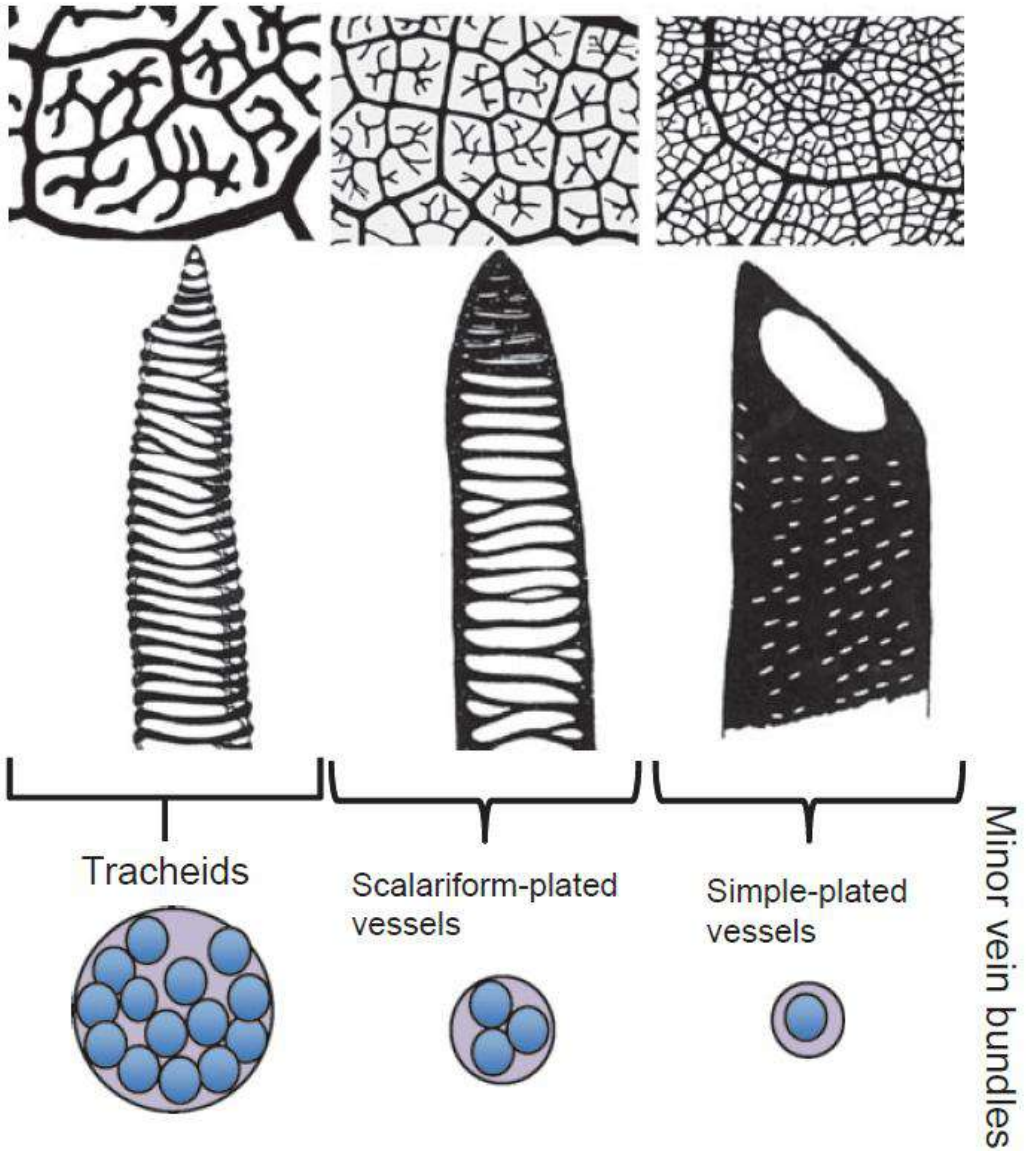
+ g_m

↑ hydraulic capacity

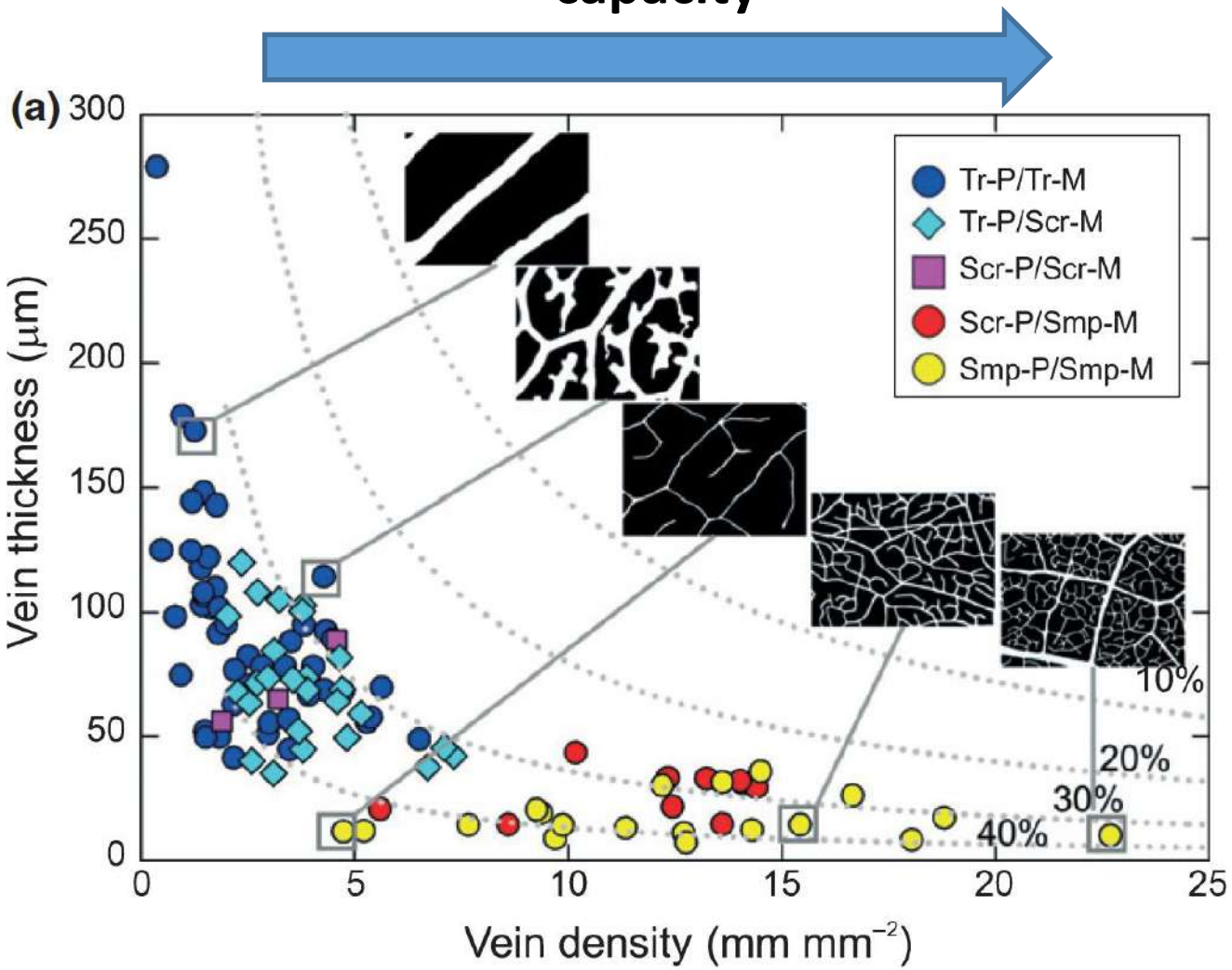
Increase in maximum stomatal conductance



Hydraulic capacity



Increase in maximum hydraulic capacity

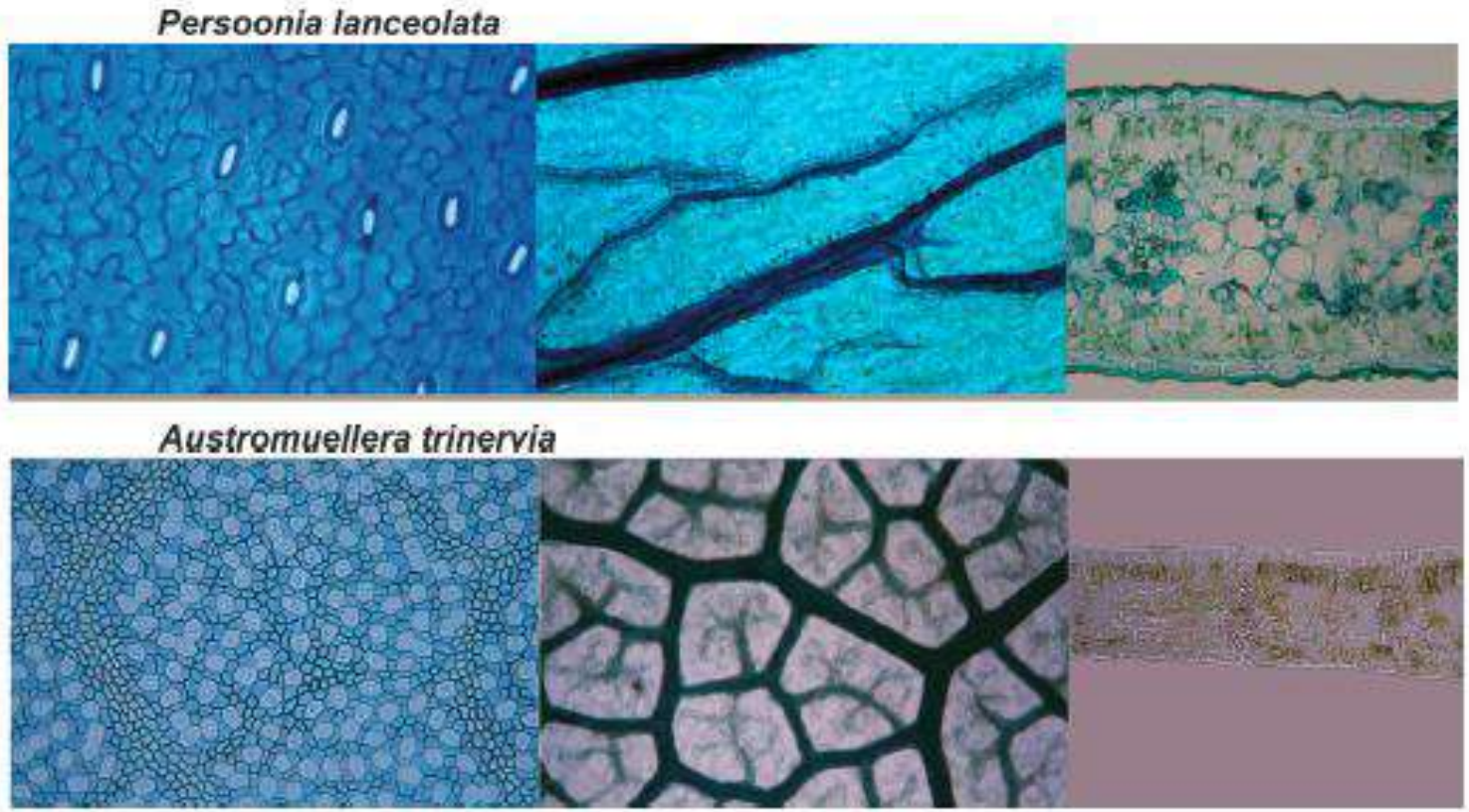


New Phytologist

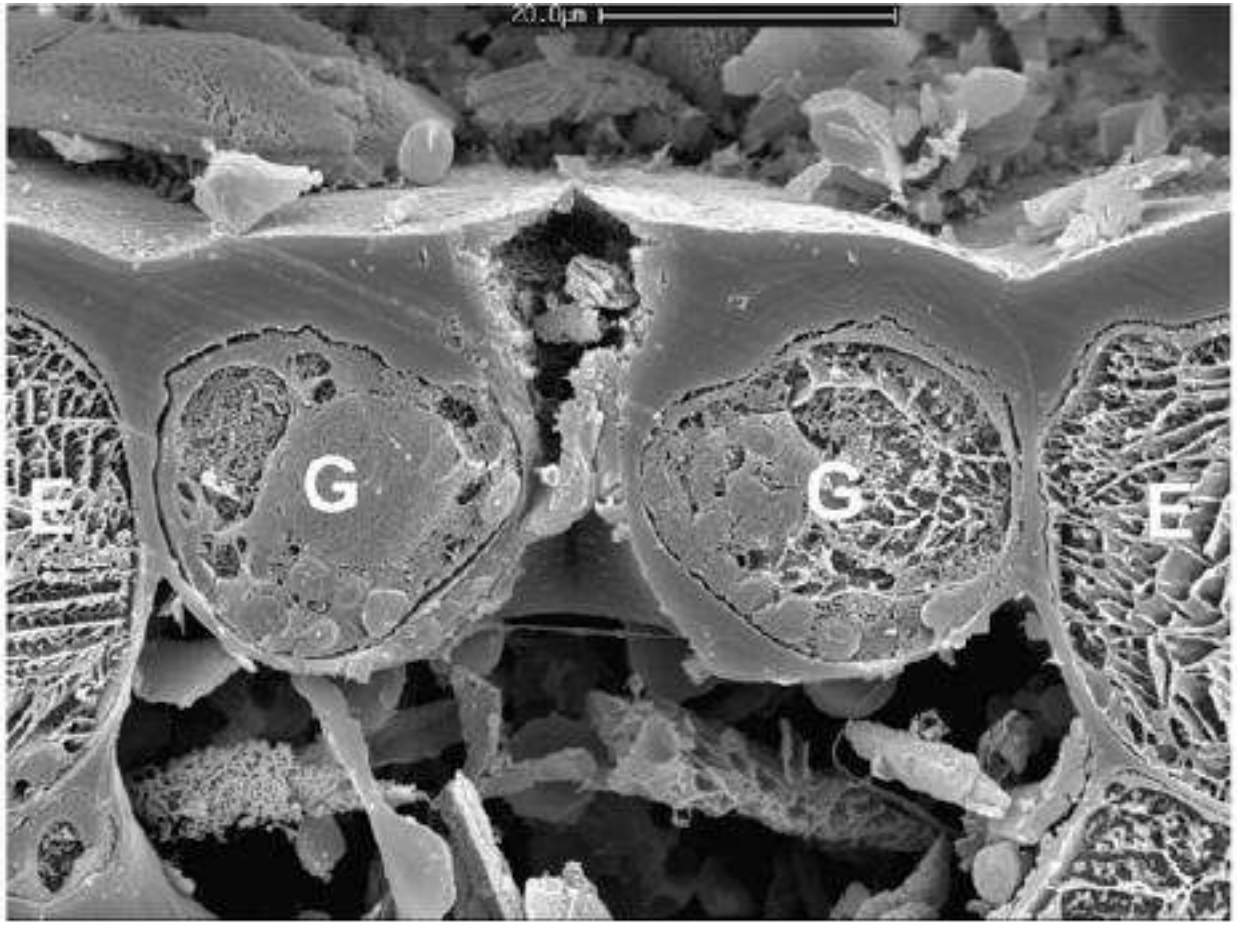
Research

Unified changes in cell size permit coordinated leaf evolution

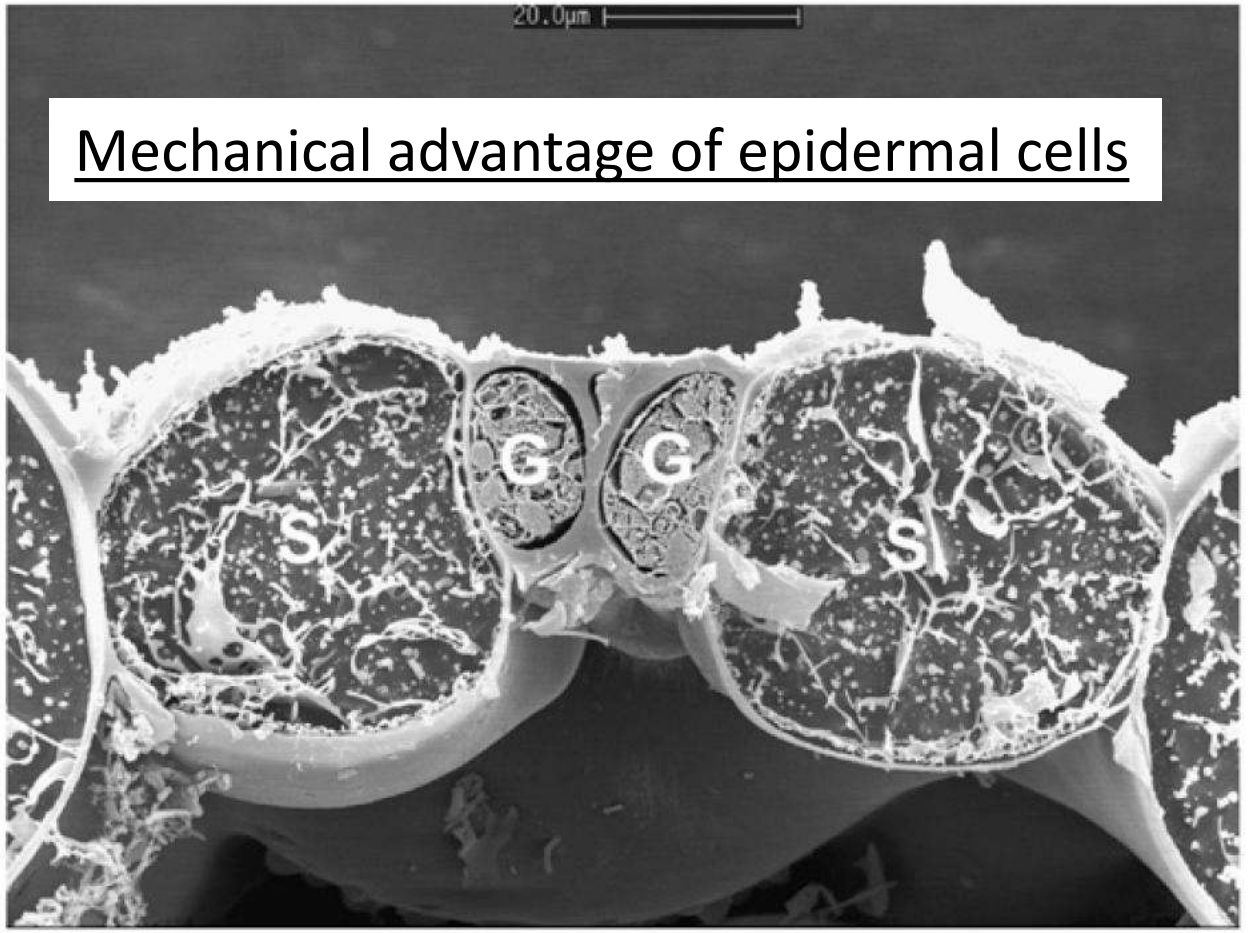
Tim J. Brodribb[1], Greg J. Jordan[1] and Raymond J. Carpenter[2]



The “unexpected” secondary effect of minituarisation



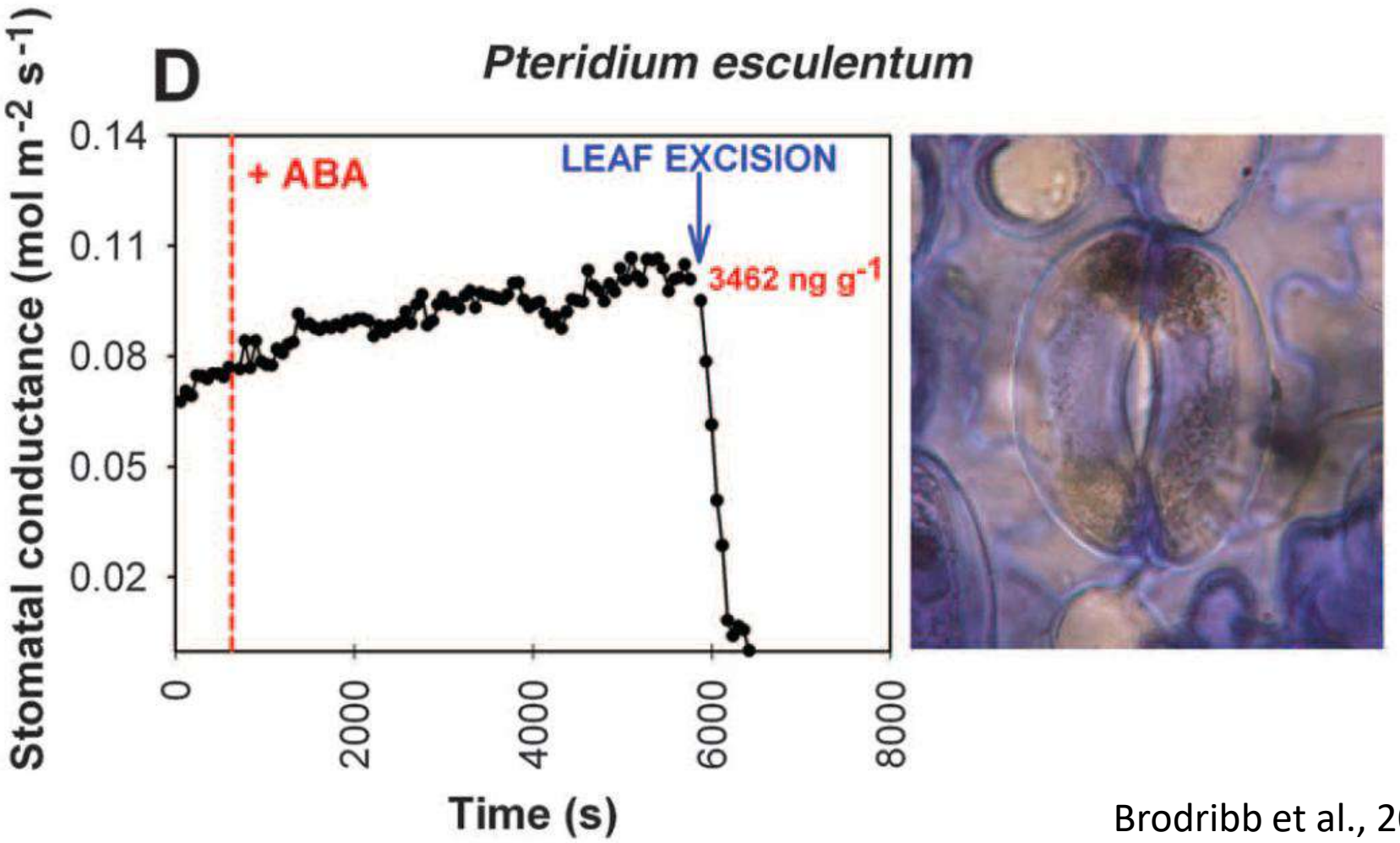
Fern



Angiosperm

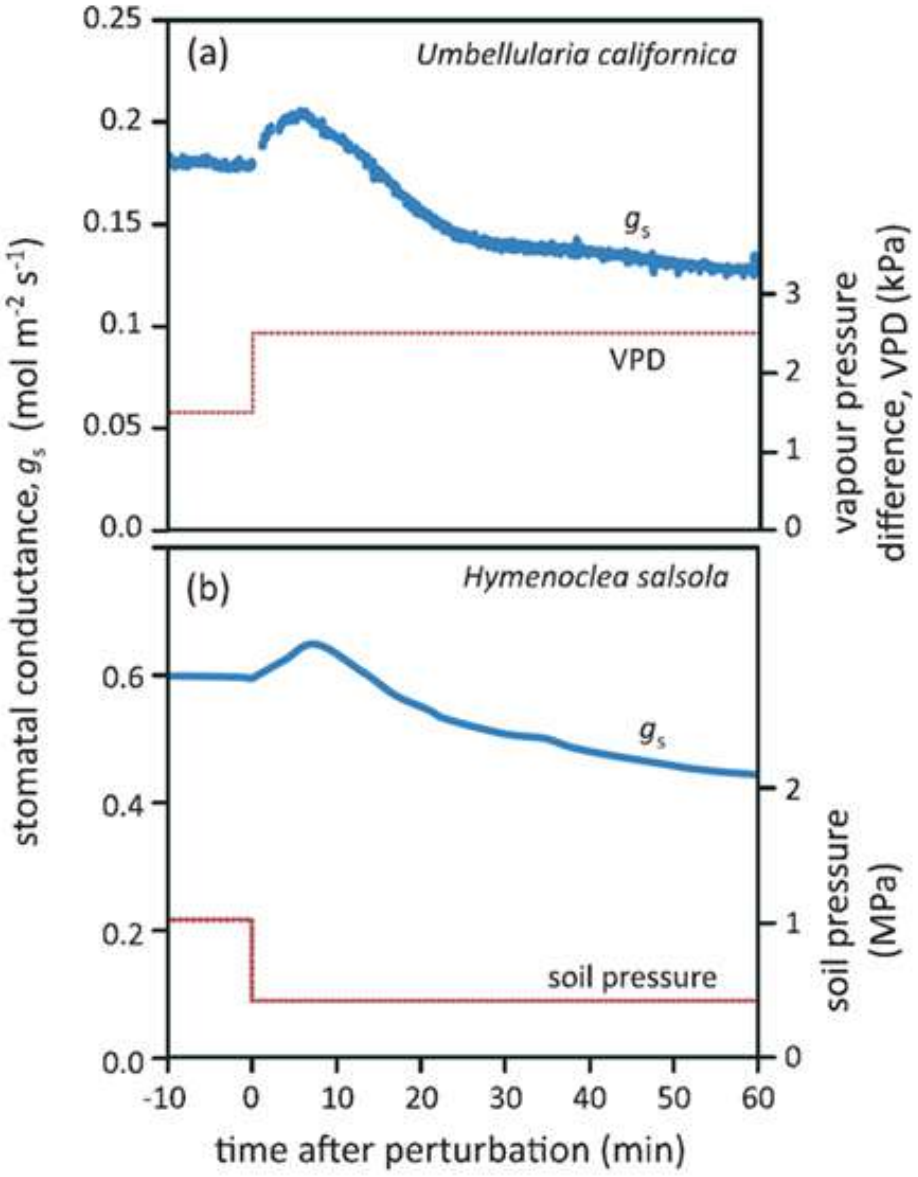
Franks and Farquhar, 2007

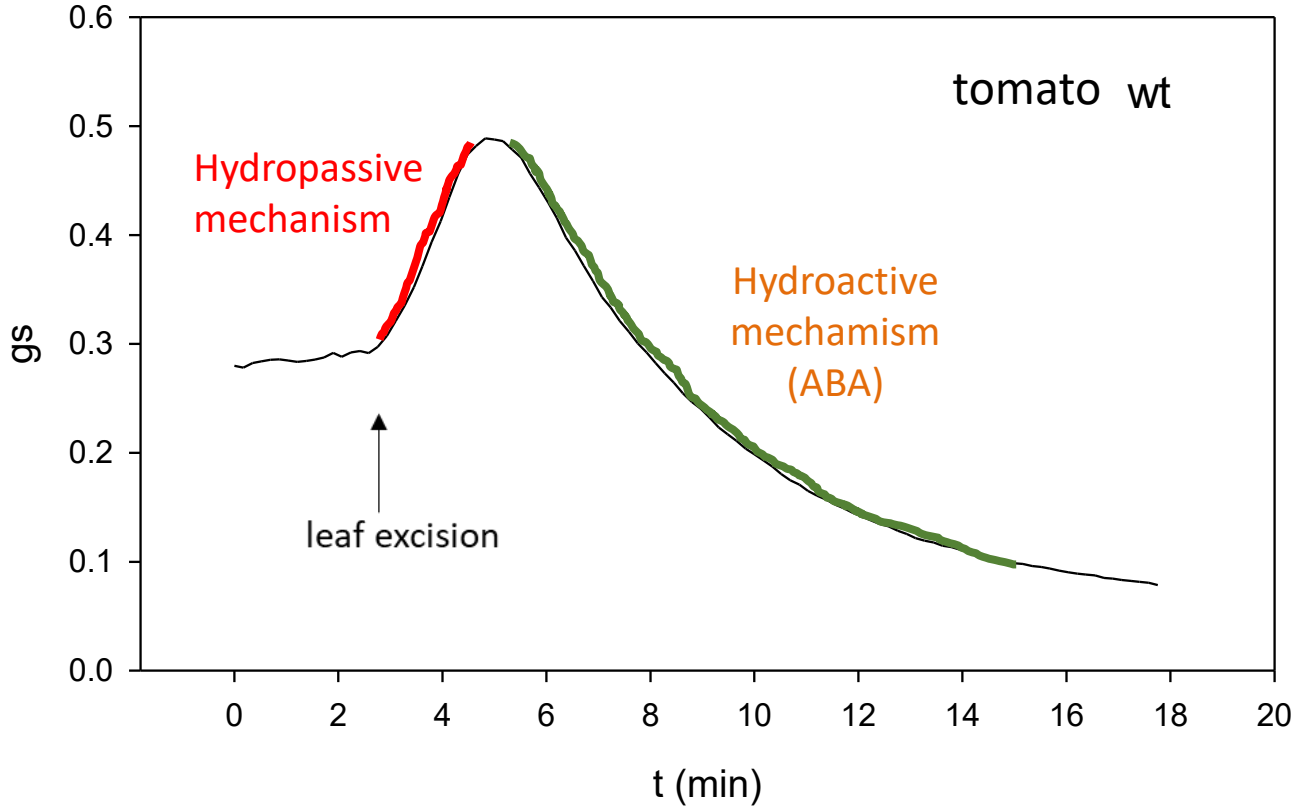
Ferns do not have an hydroactive mechanism (nor they need it)

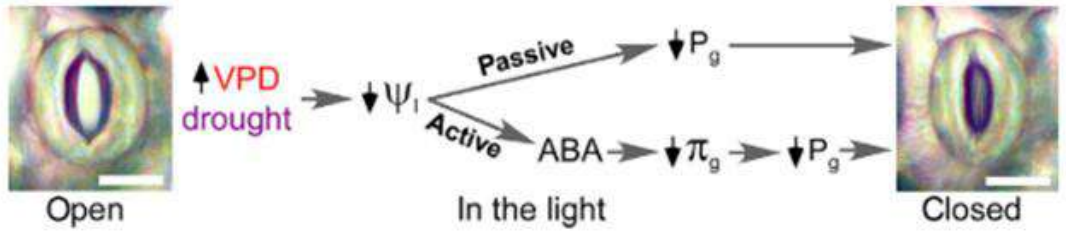


Brodribb et al., 2011

Wrong-way responses







Sussmilch et al 2017

Pteridophytes



Gymnosperms



Angiosperms



Hydropassive mechanism

Response to ABA

Hydroactive mechanism → ABA

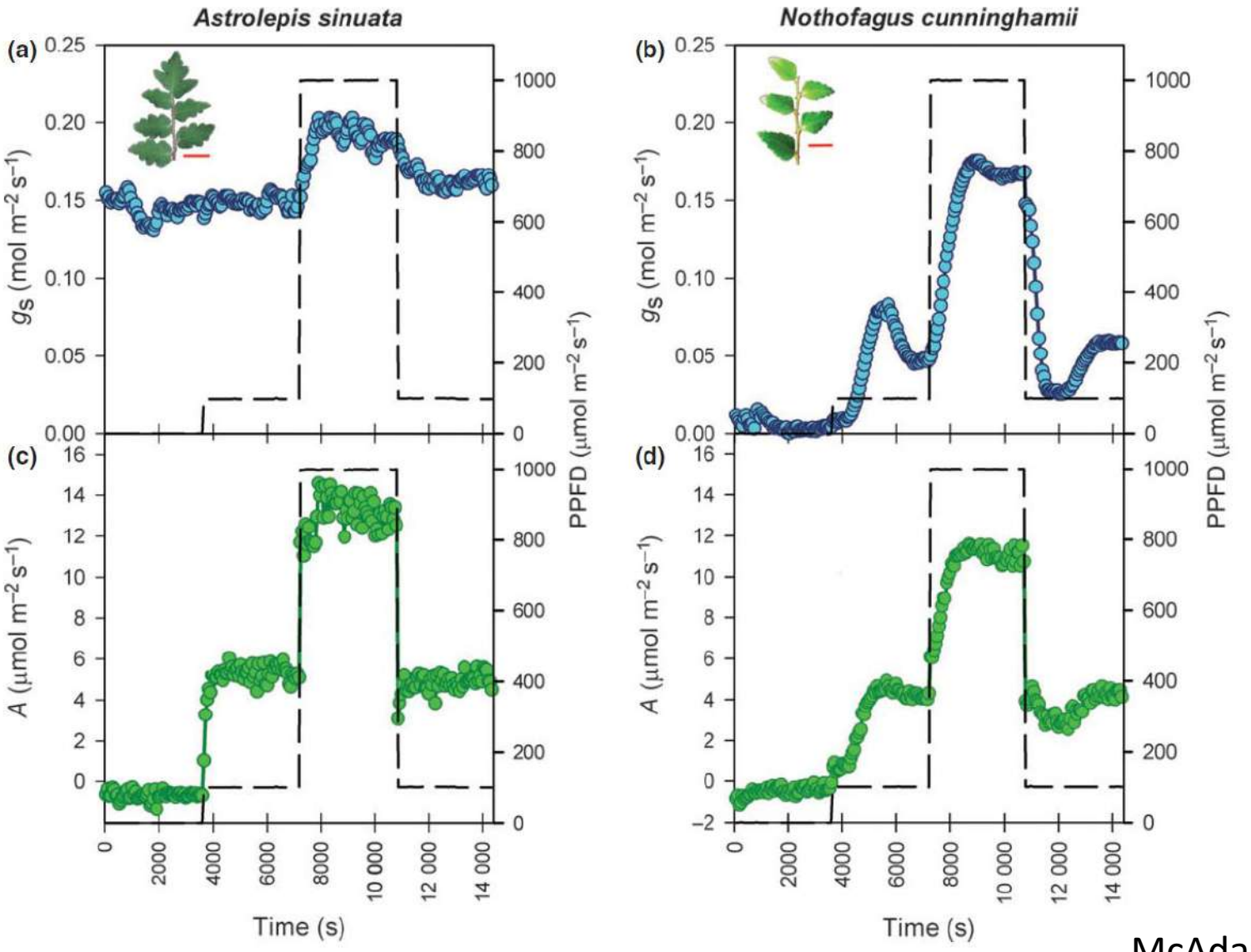
Why was this hydroactive mechanism necessary?

Hypothesis 1. Fast-growing or "unexpected" secondary effect

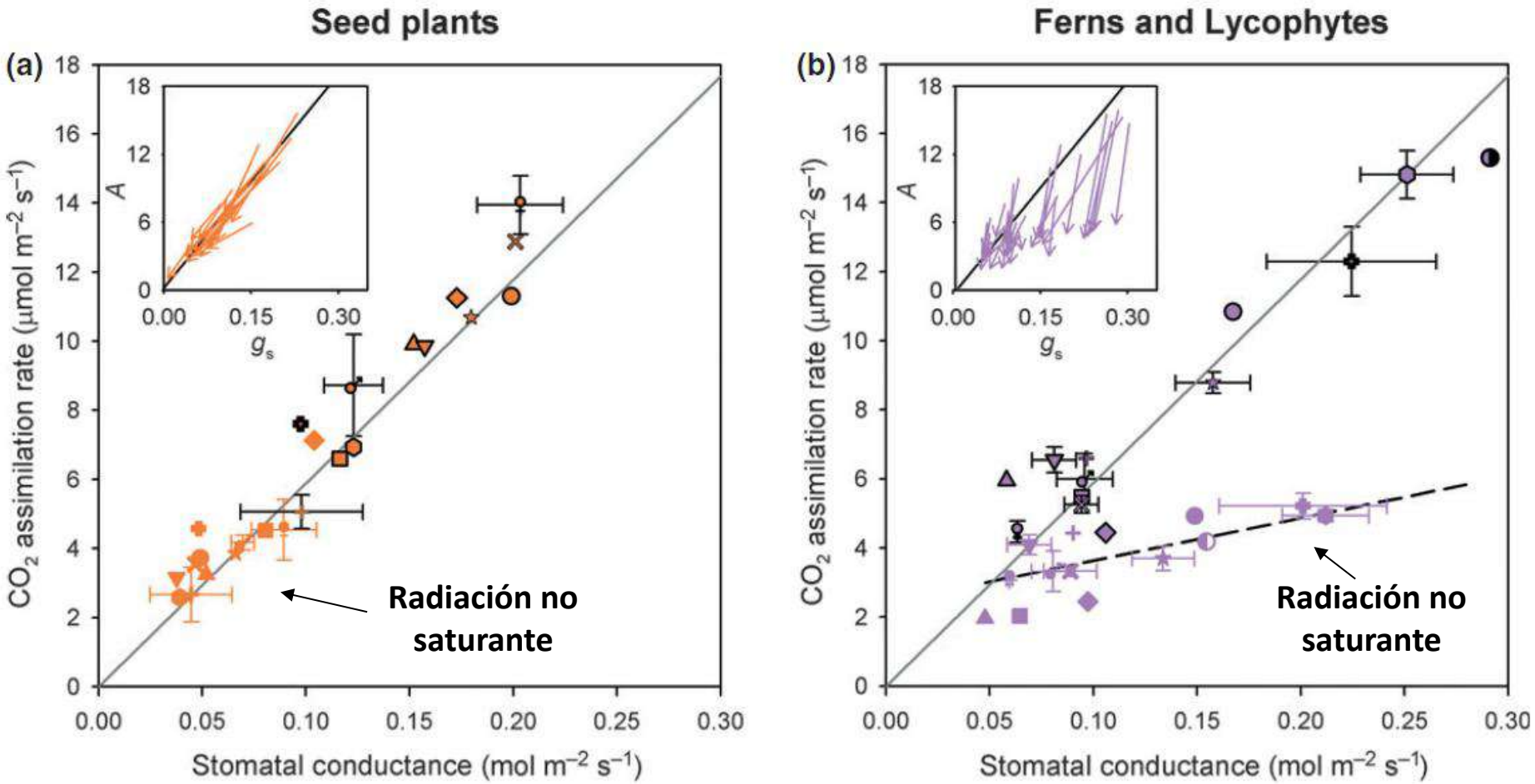
Hypothesis 2. Coordination of An-gs

Pteridofitas

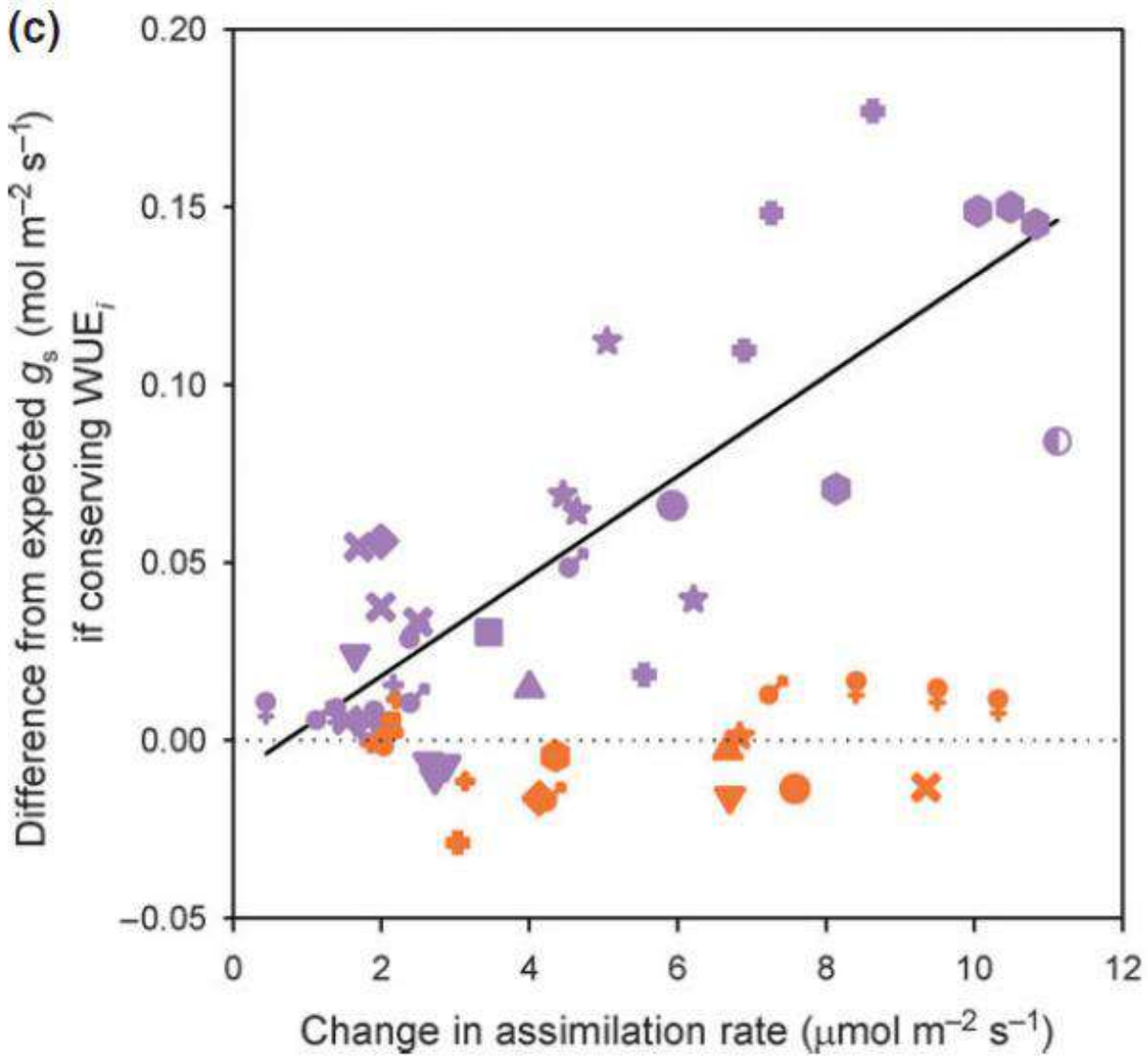
Angiospermas



McAdam & Brodribb 2012



McAdam & Brodribb 2012



Ferns

Seed plants

McAdam & Brodribb 2012

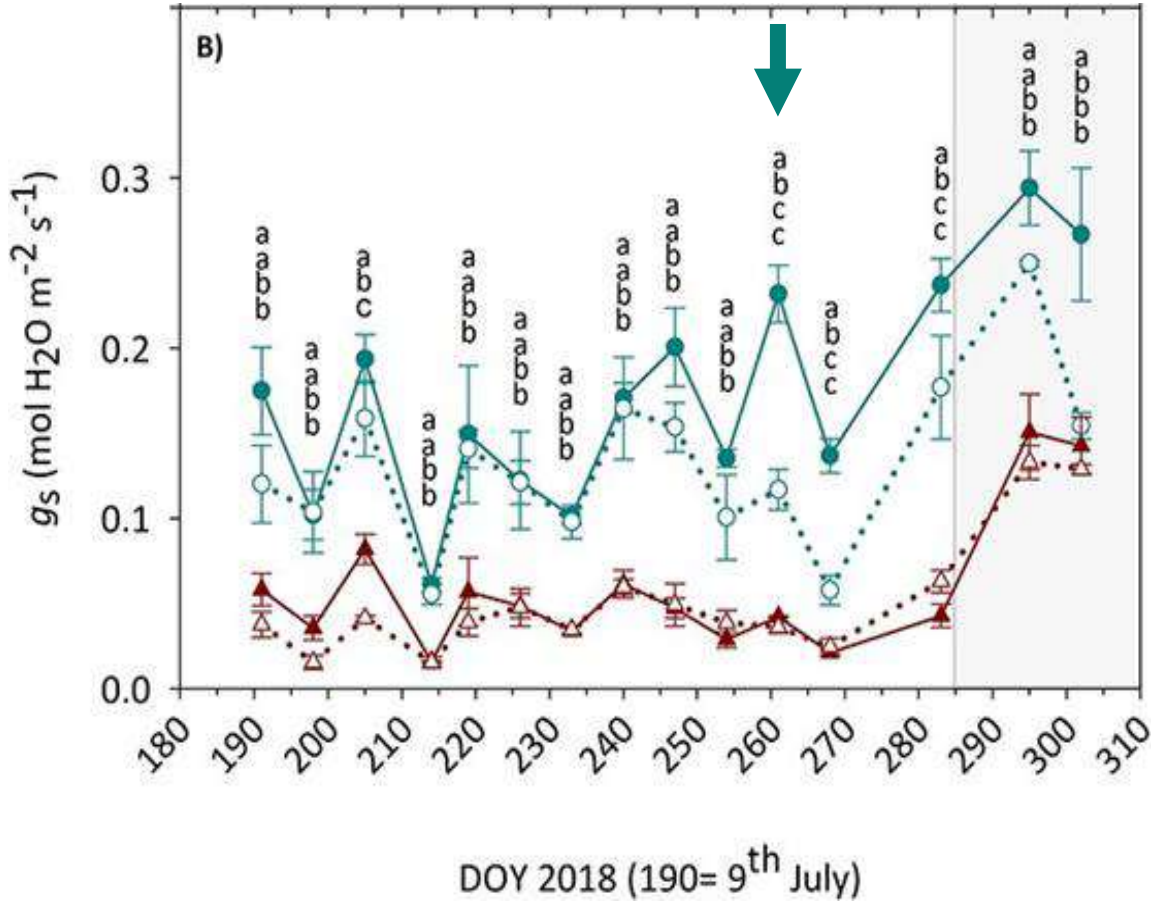
When the hydropassive mechanism is not enough

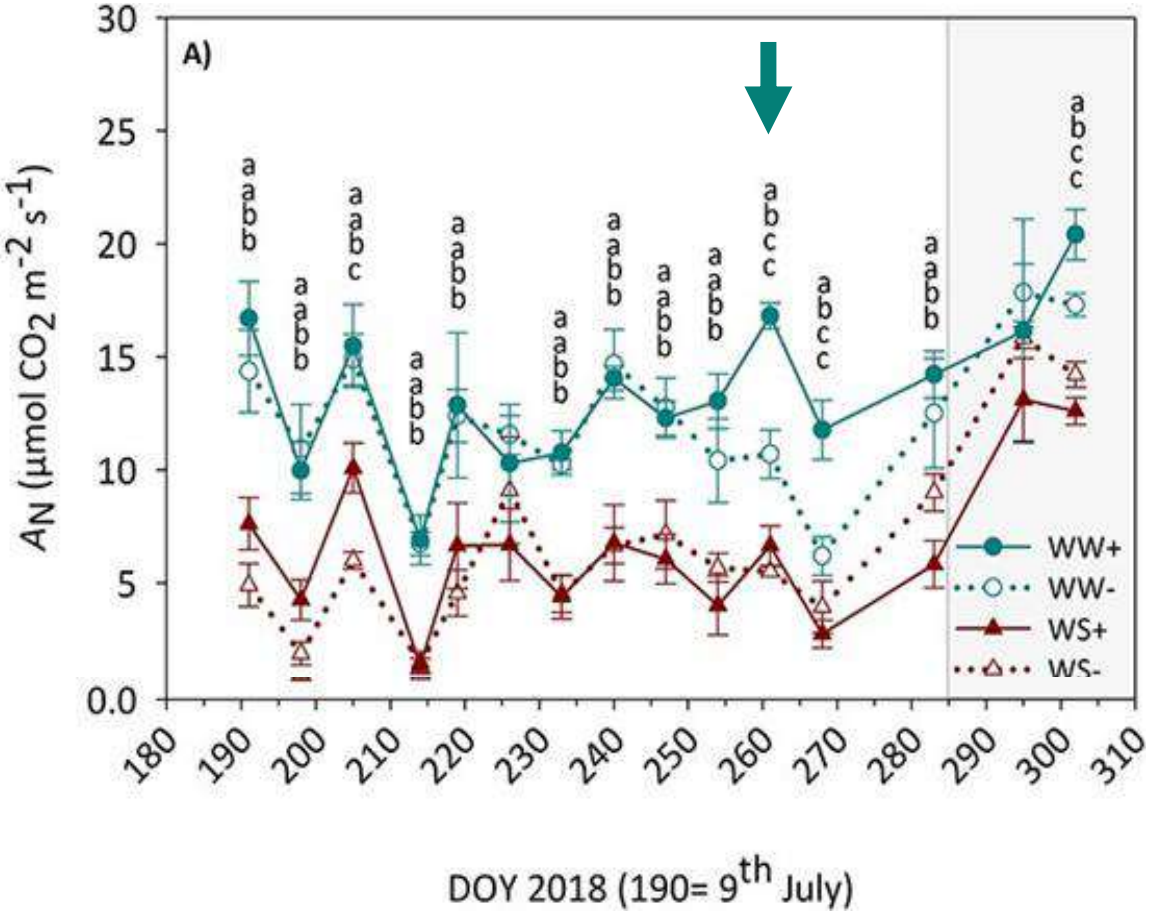


Fruitless (-)



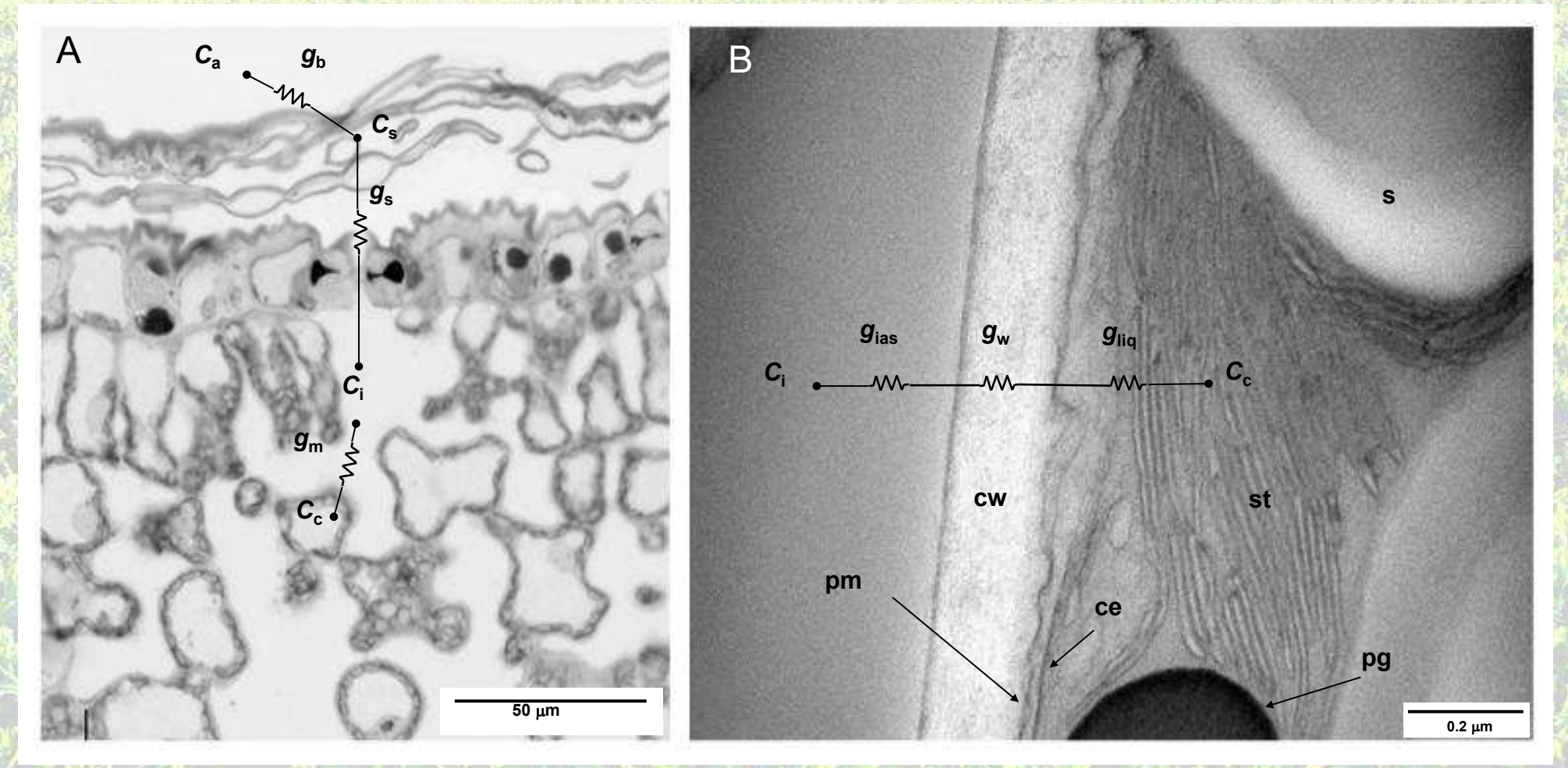
Fruit bearing (+)



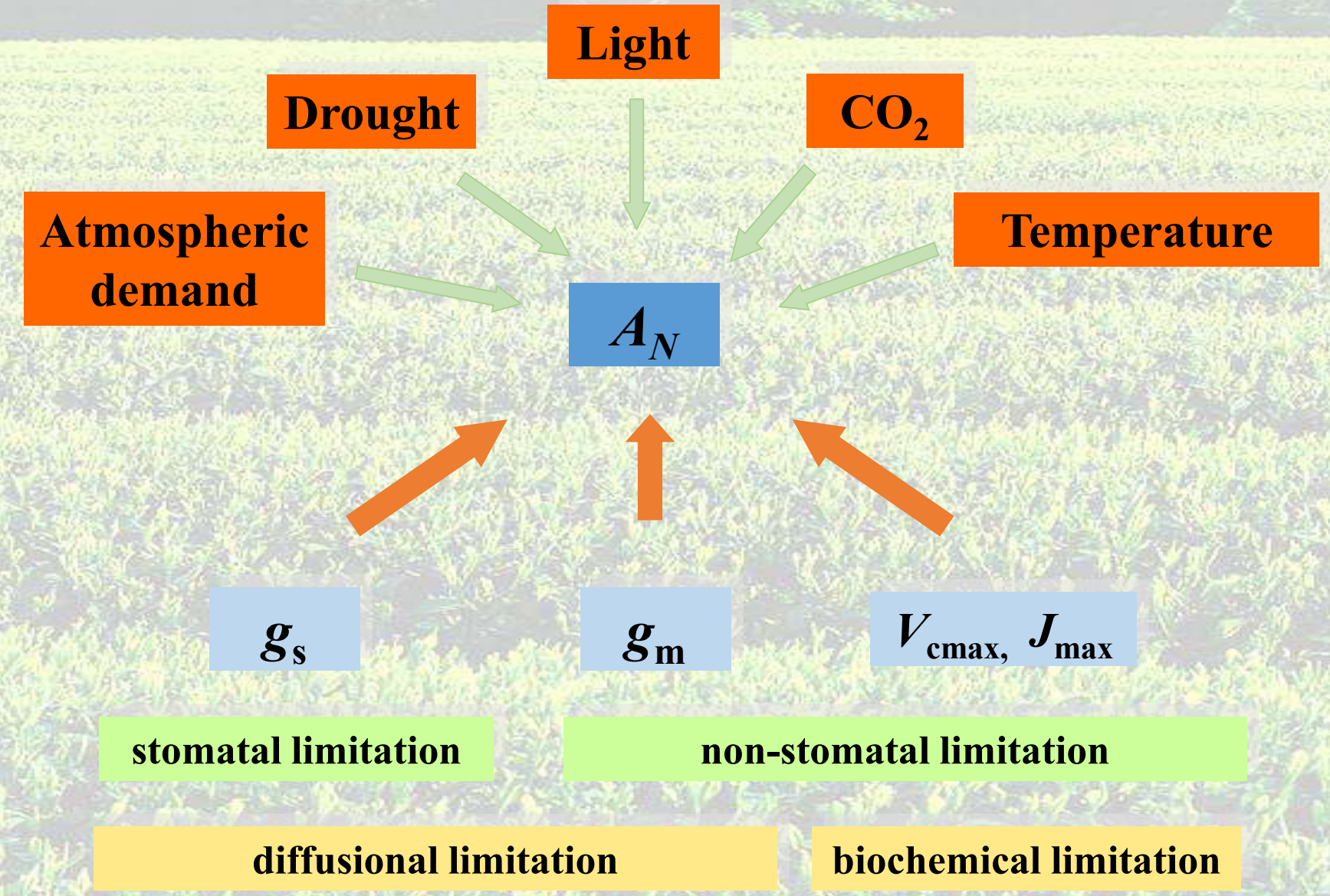


Another actor in the diffusional limitations to CO2

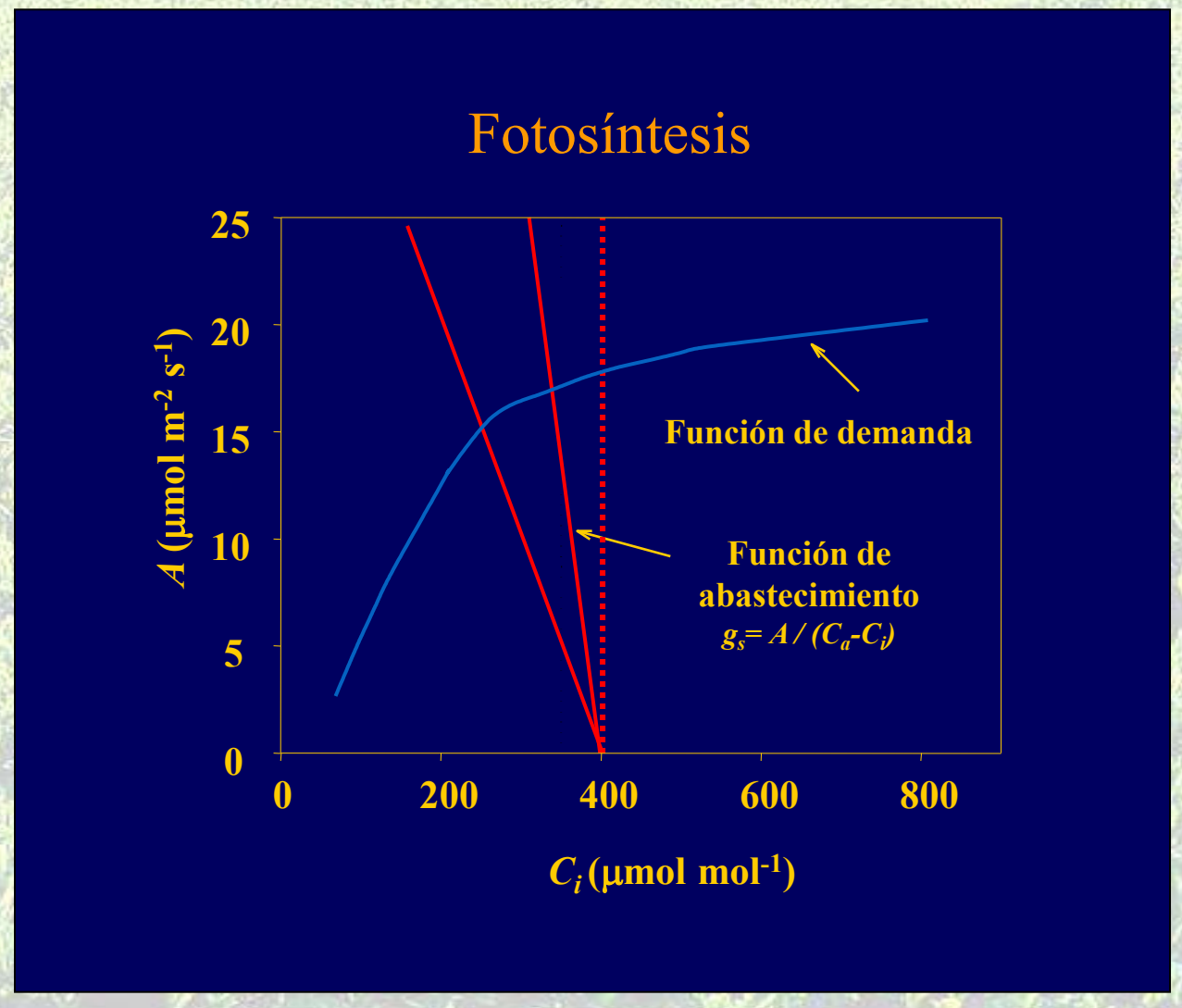
Mesophyll conductance to CO2

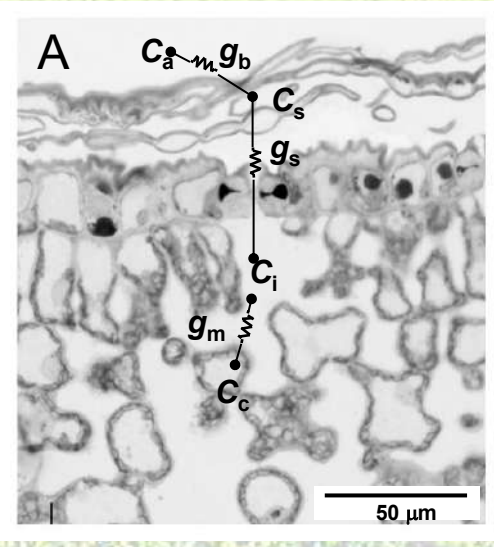


Olivo y vid (fotos A. Díaz, 2007)


Light
Drought
CO_2
Atmospheric demand
Temperature
A_N
g_s
g_m
V_{cmax}, J_{max}
stomatal limitation
non-stomatal limitation
diffusional limitation
biochemical limitation

Supply and demand curves for photosynthesis



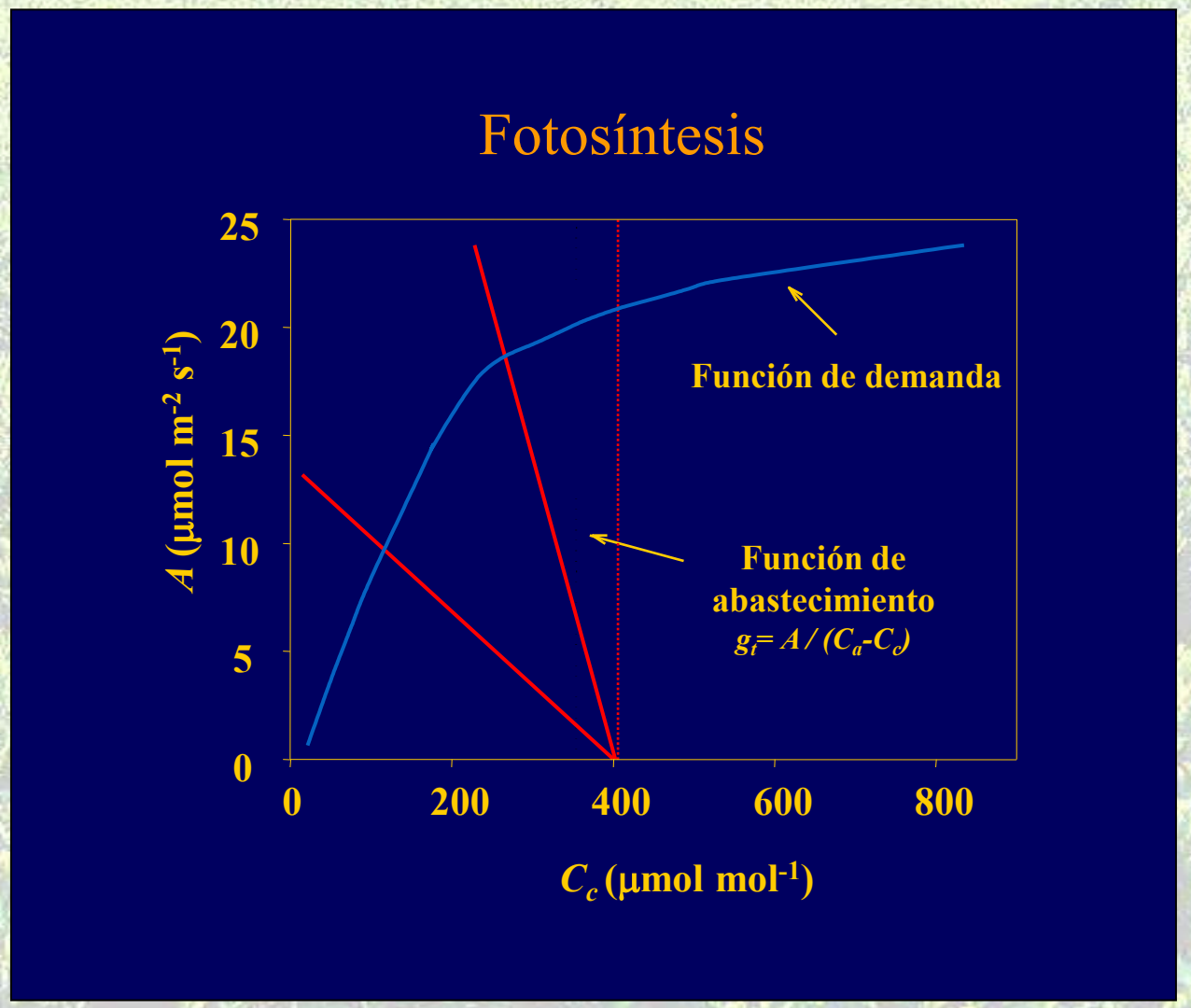


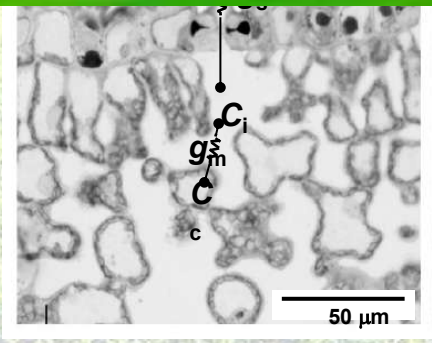
Fick´s law

$A = g_{sc} (C_a - C_i)$

$g_{sc} = g_{sw} / 1.6$

Supply and demand curves for photosynthesis





Fick´s law

$A = g_{sc} (C_a - C_i)$

$A = g_m (C_i - C_c)$

$C_i = C_a - A/g_{sc}$

$C_c = C_i - A/g_m$

$C_c = C_a - A/g_{sc} - A/g_m$

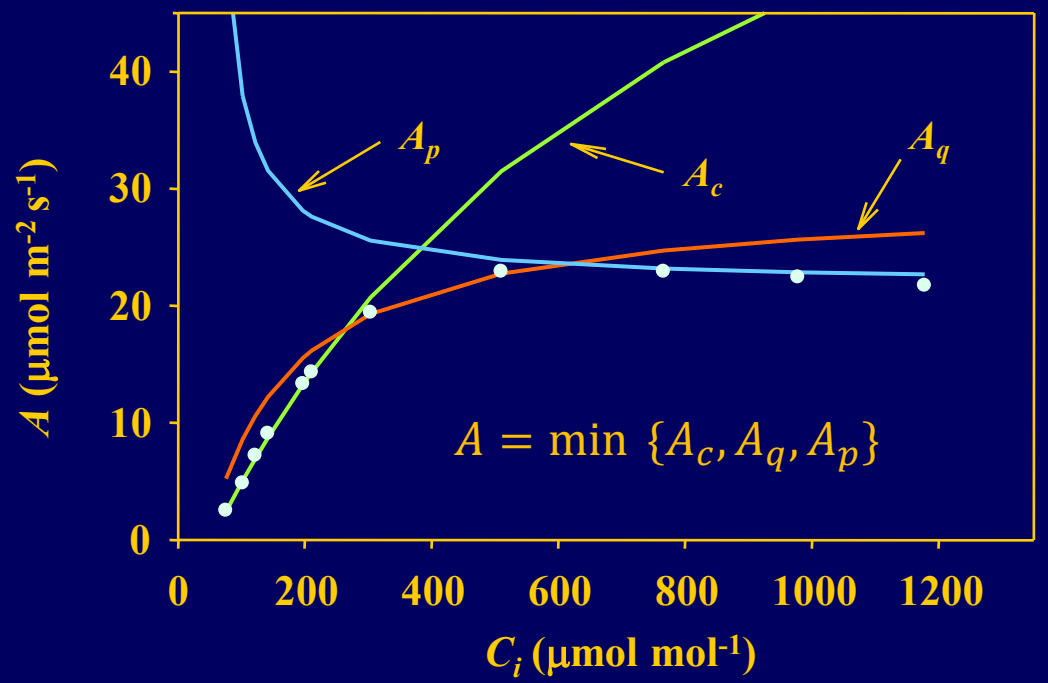
$C_c = C_a - A (1/g_{sc} + 1/g_m)$

$1/g_t = 1/g_{sc} + 1/g_m$

$g_t = A/(C_a - C_c)$

A-Ci curves analysis

Modelo de fotosíntesis de Farquhar



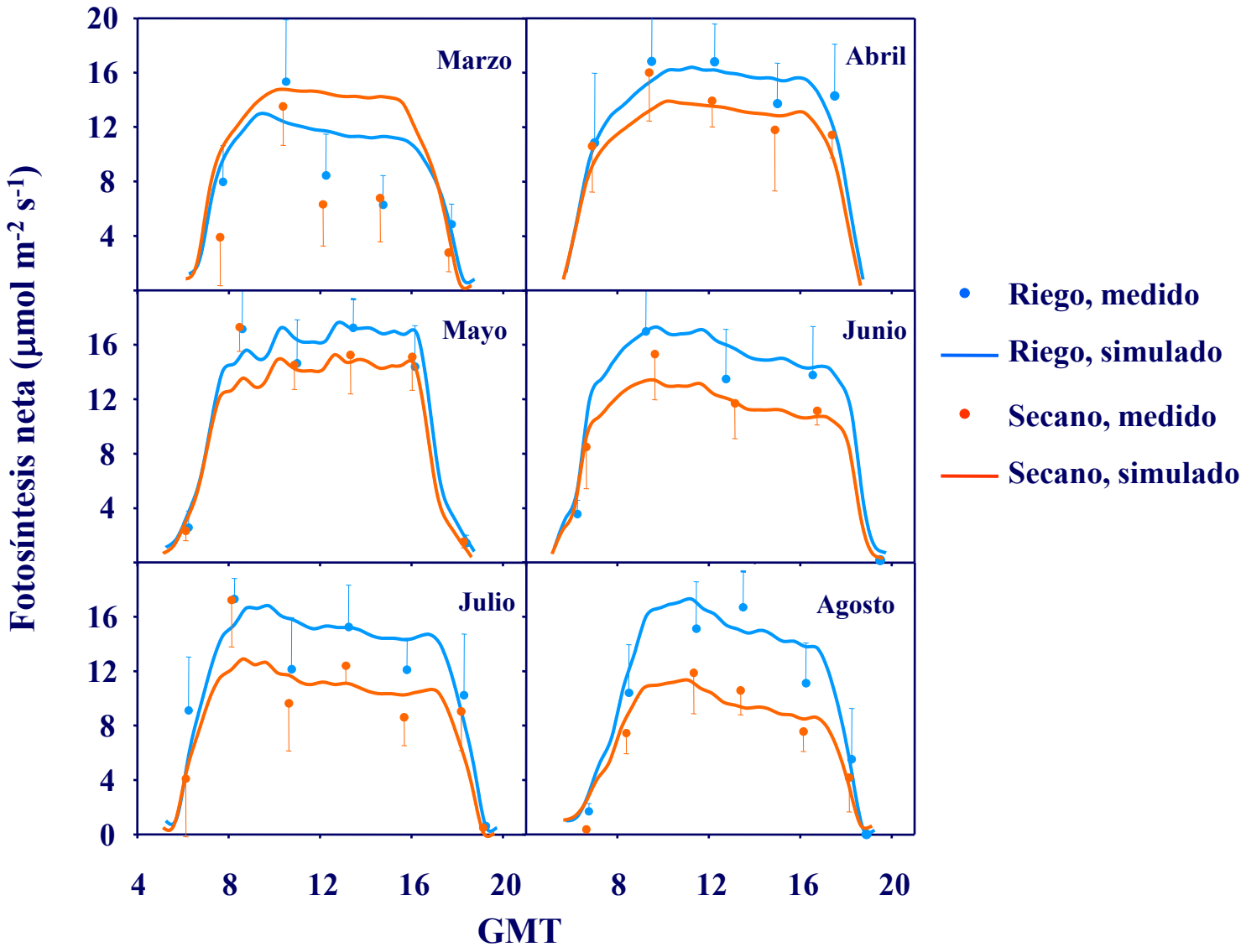
$$A_c = V_{cmax} \frac{C_i - \Gamma^*}{C_i + K_c(1 + (o_i / K_o))} - R_d$$

$$A_p = \frac{3\ TPU}{1 - (\Gamma^* / C_i)}$$

$$A_q = \frac{J(C_i - \Gamma^*)}{4(C_i + 2\Gamma^*)}$$

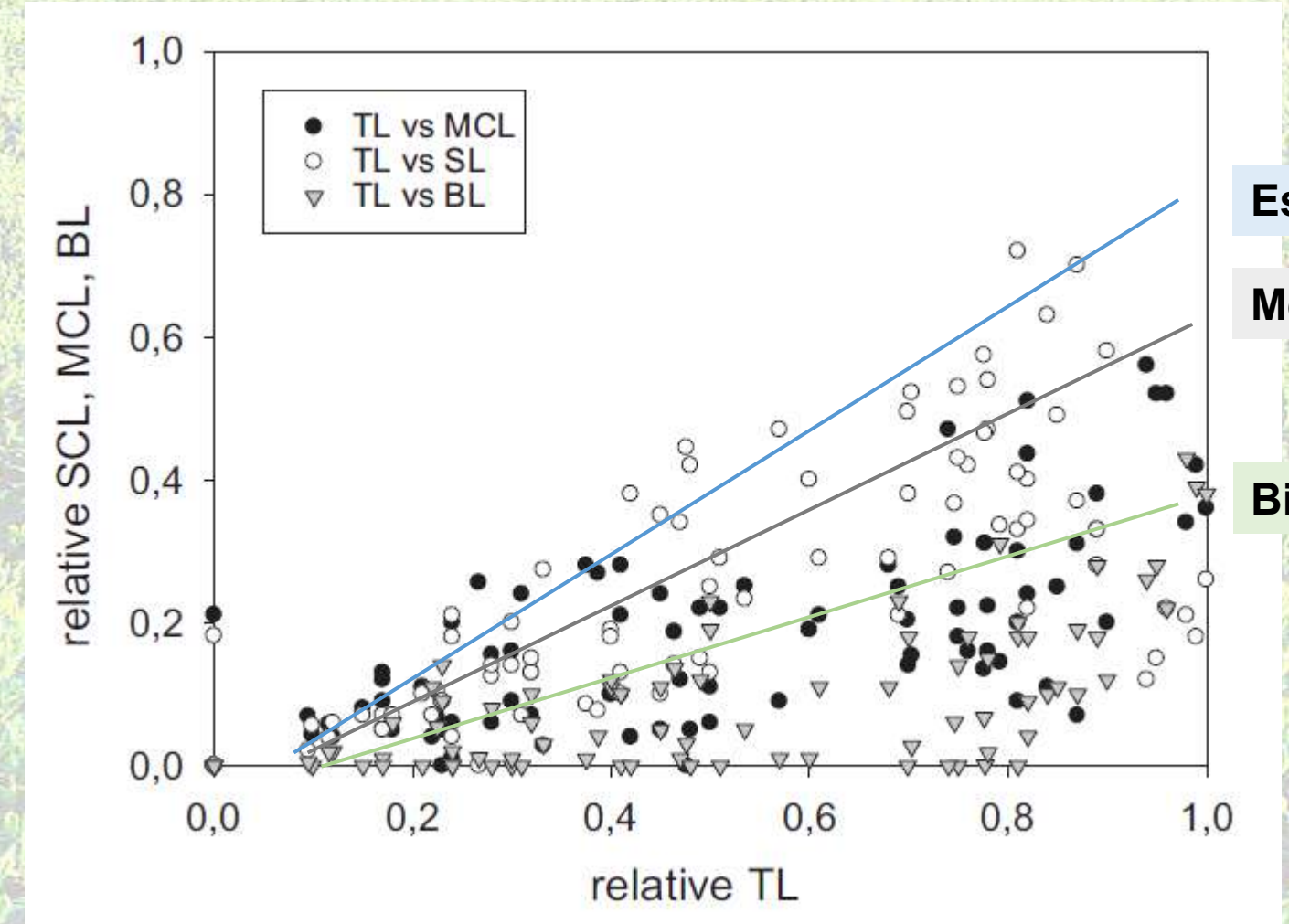
Models fit

Olive



Diffusional limitations

Collection of 32 species



Estomáticas

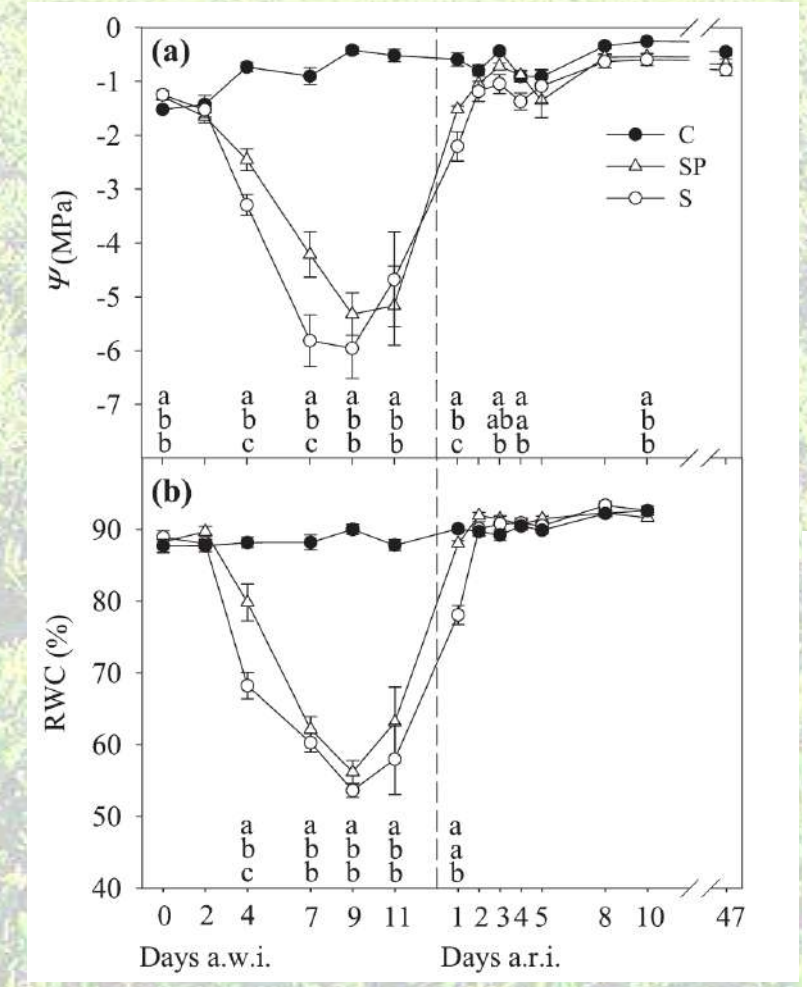
Mesófilo

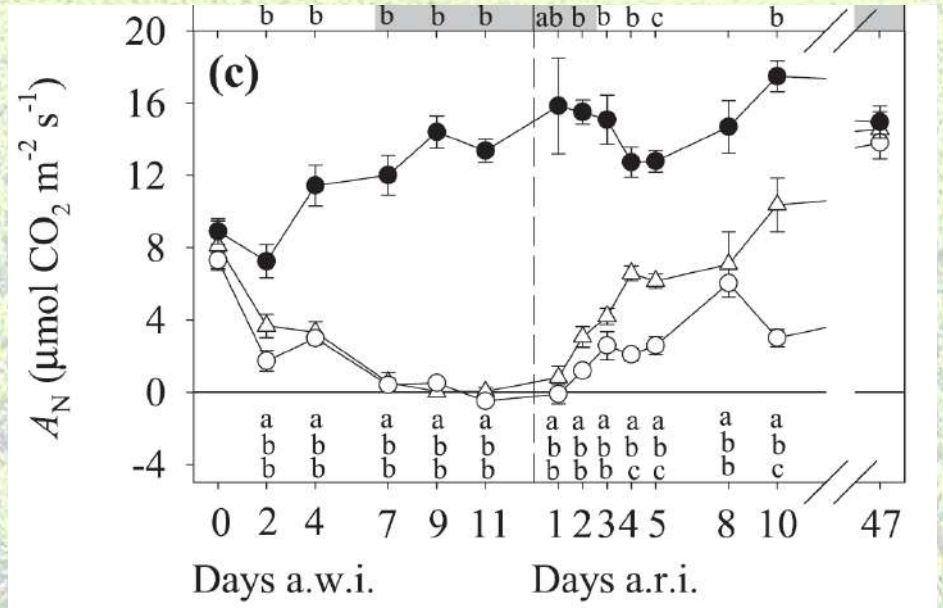
Bioquímicas

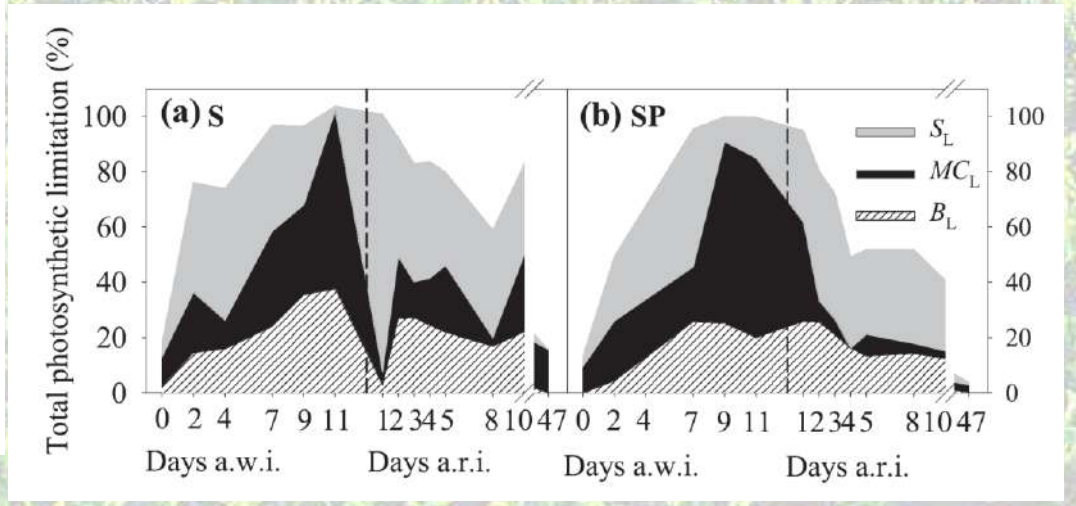
Flexas et al., PS, 2012

Diffusional limitations

Olivo

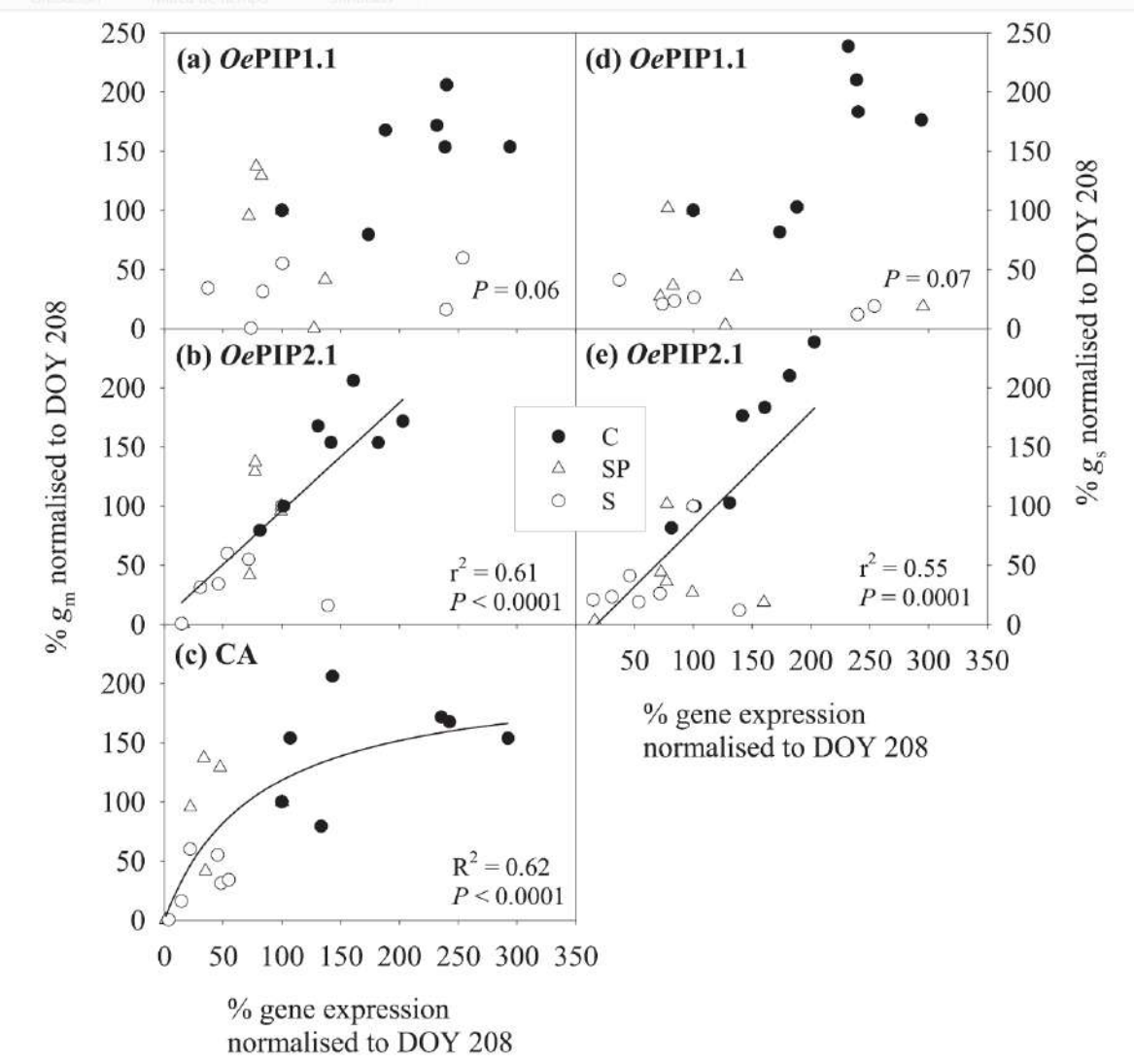




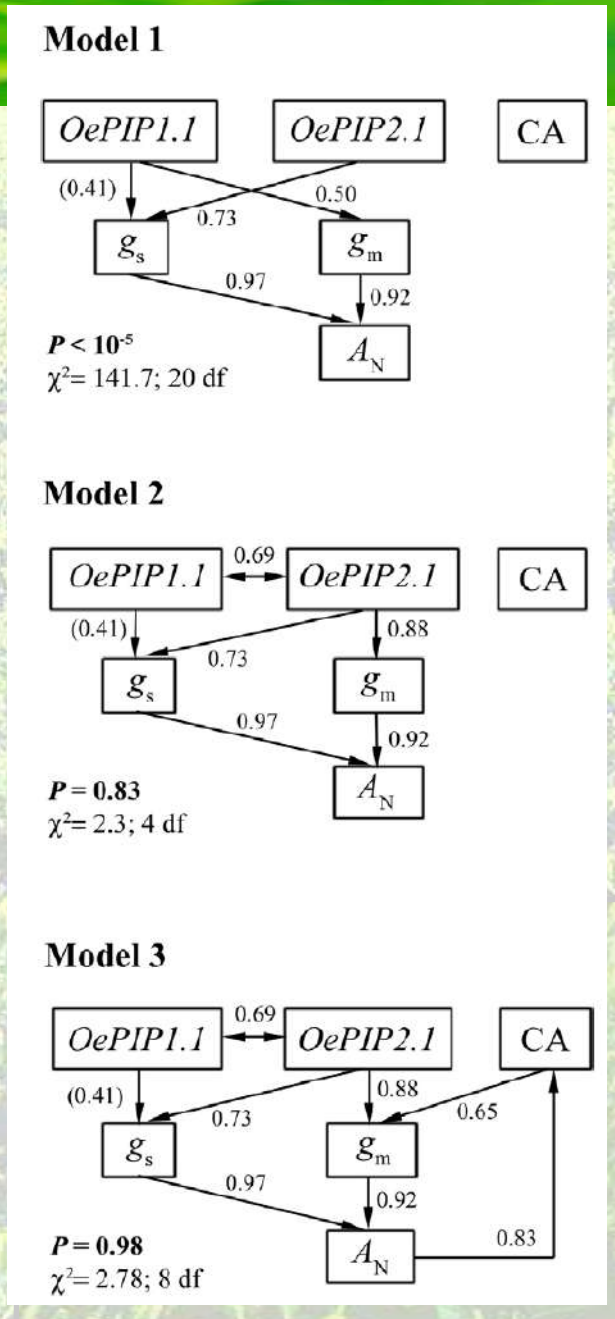


Perez-Martin et al., JEB, 2015

Aquaporins & carbonic anhydrase

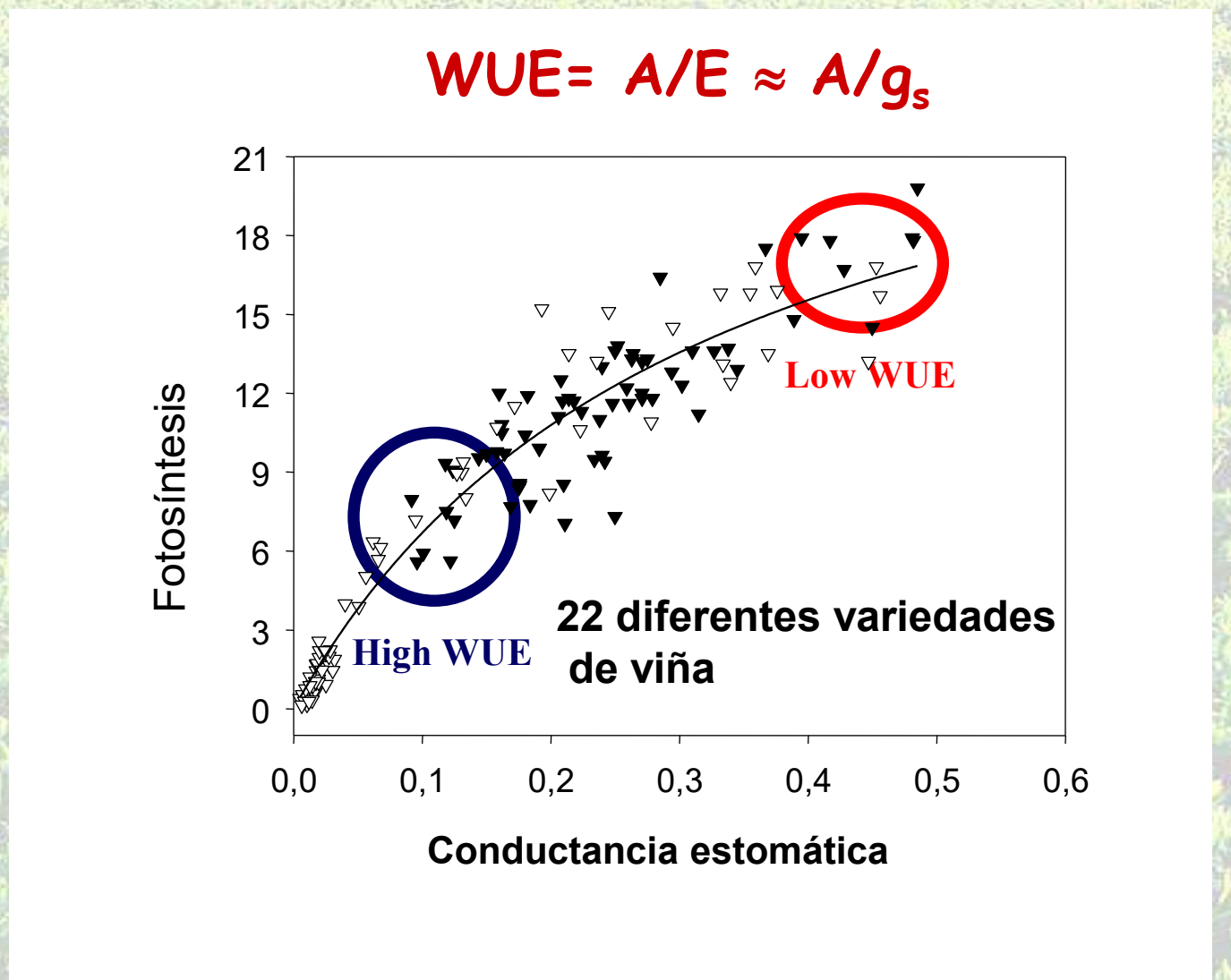


Perez-Martin et al., JEB, 2015



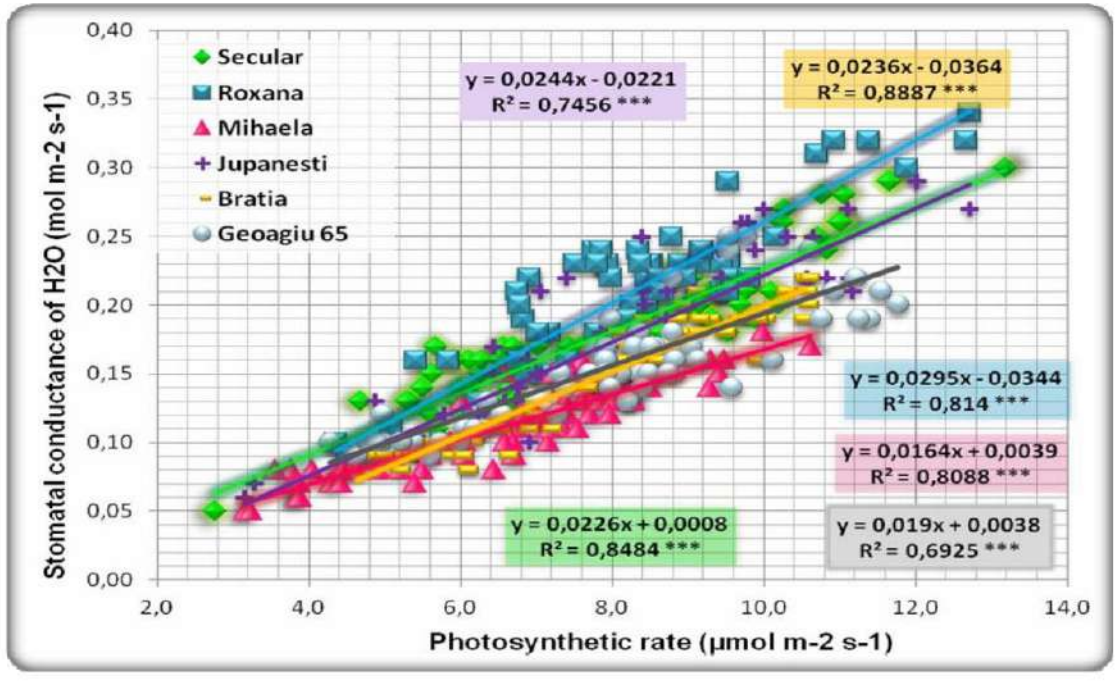
Photosynthesis vs Stomatal conductance

The cost of the transpiration control



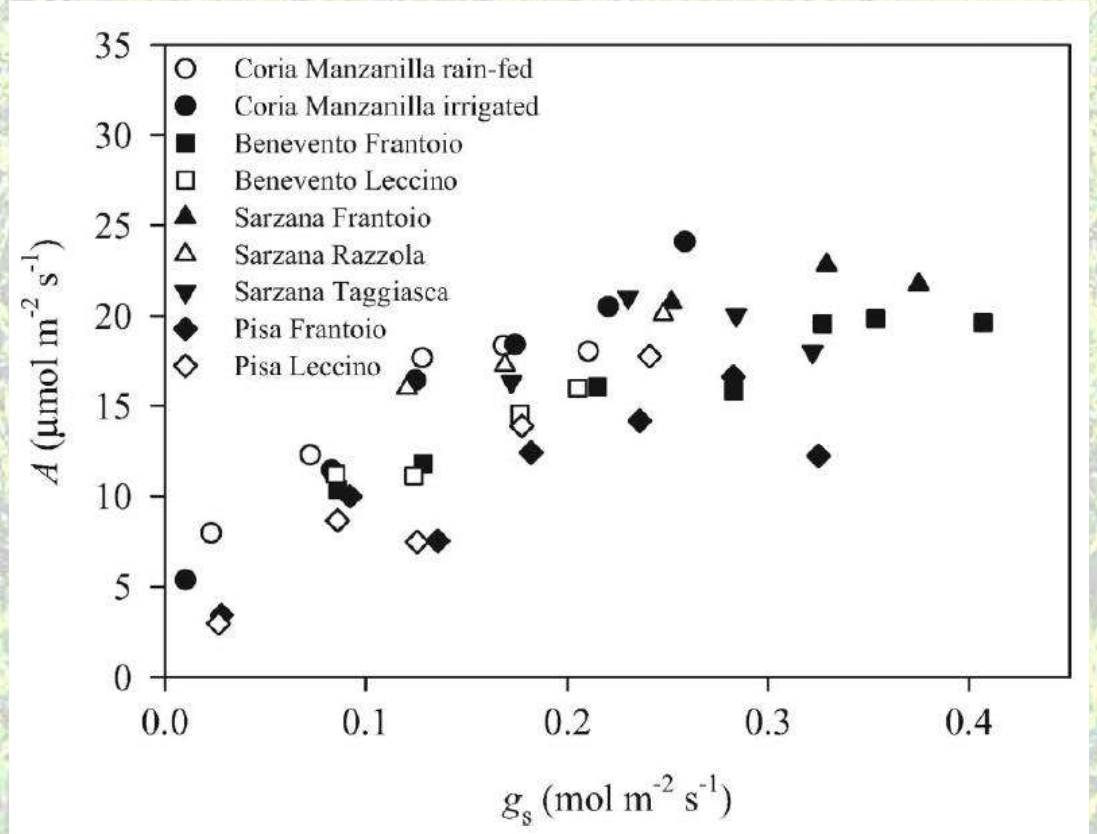
Photosynthesis vs Stomatal conductance

Walnut cultivars



Ancu et al., 2014

Olive cultivars

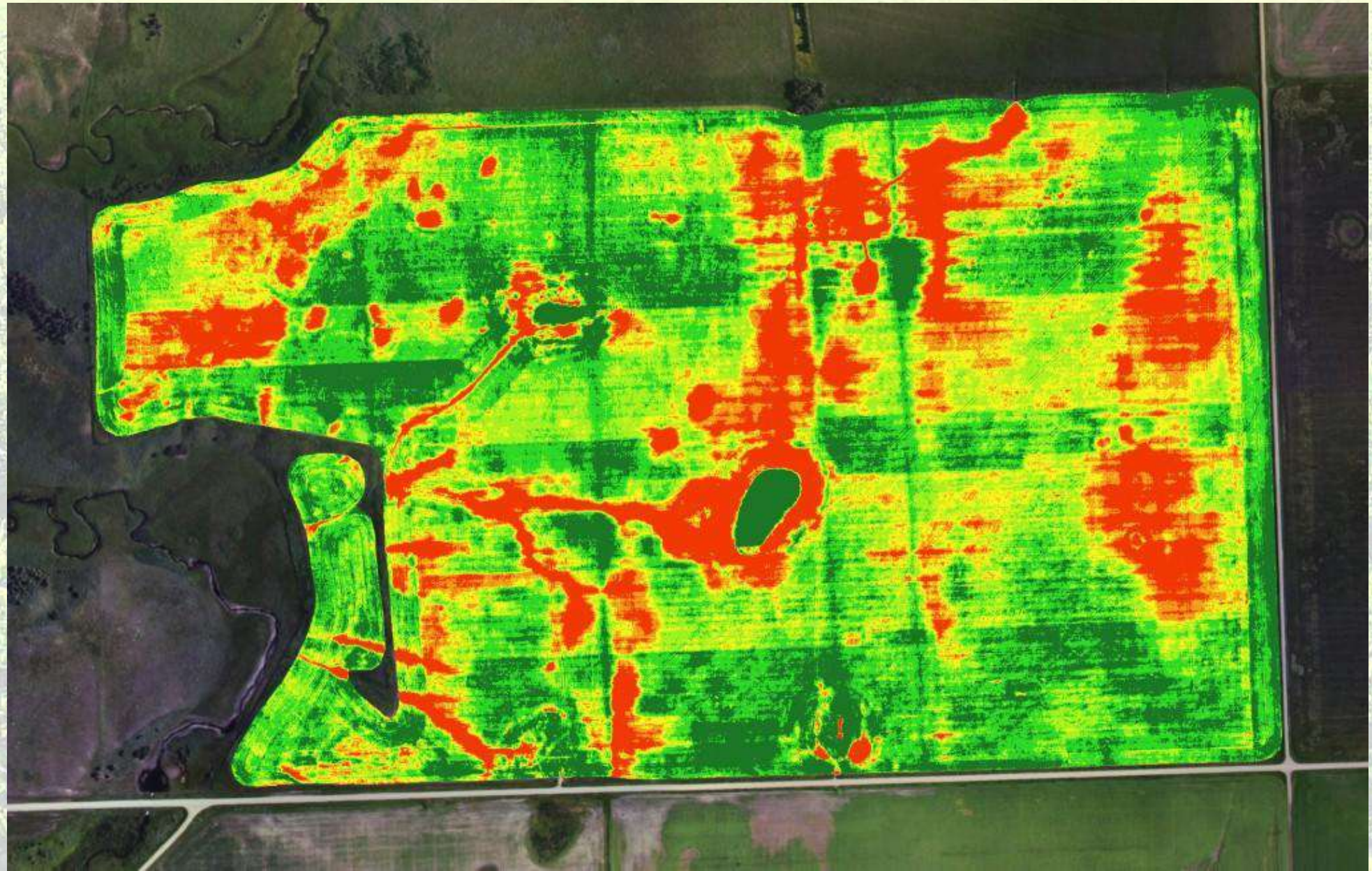


Fernandez et al., 2008

Energy balance



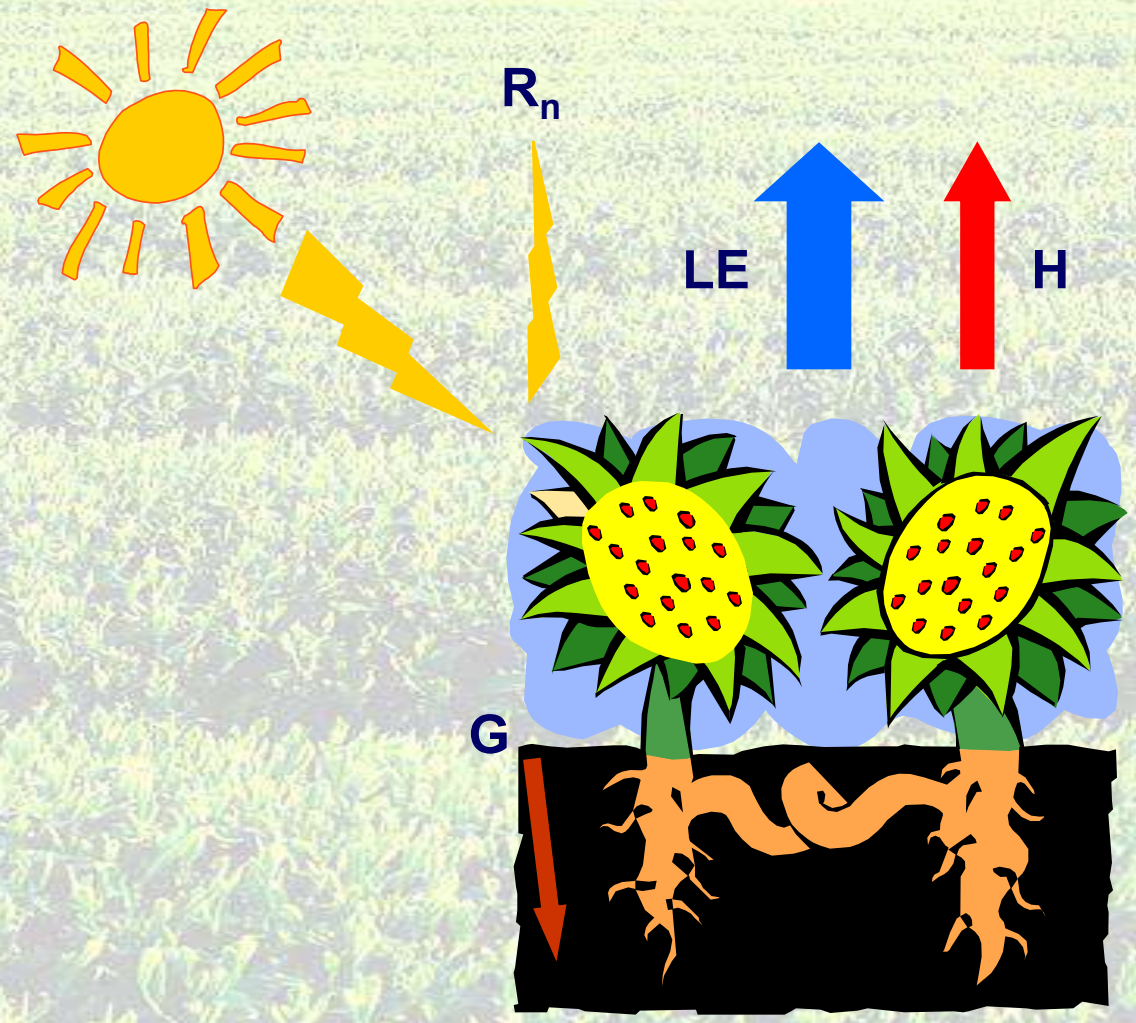
Use of thermal images



Use of thermal images



Energy balance



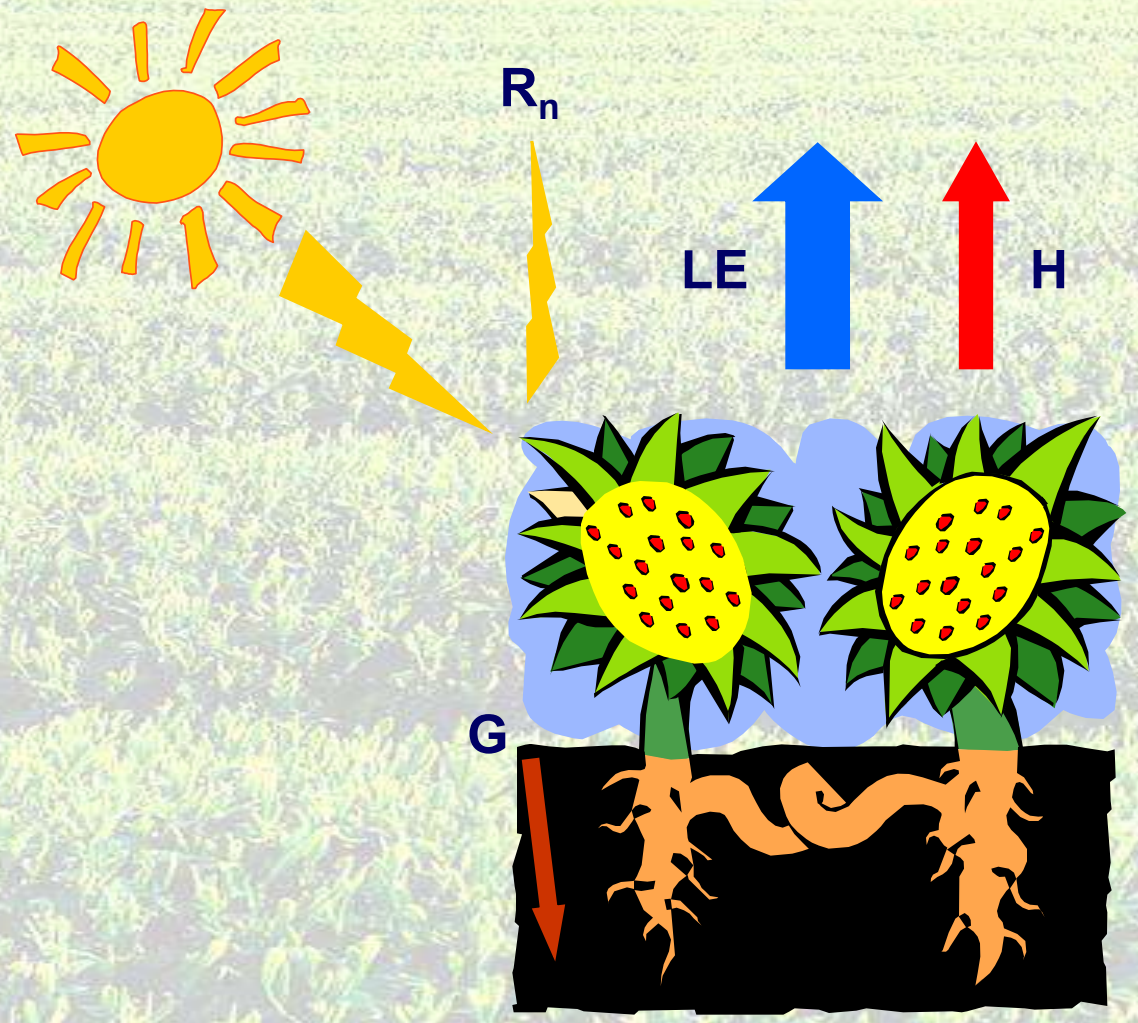
Balance energía

$R_n = LE + H + G$

Rn = net radiation
LE= latent heat flux (transpiration)
H= sensible heat flux (heat)
G= soil heat flux

A key variable is the surface temperature

Energy balance



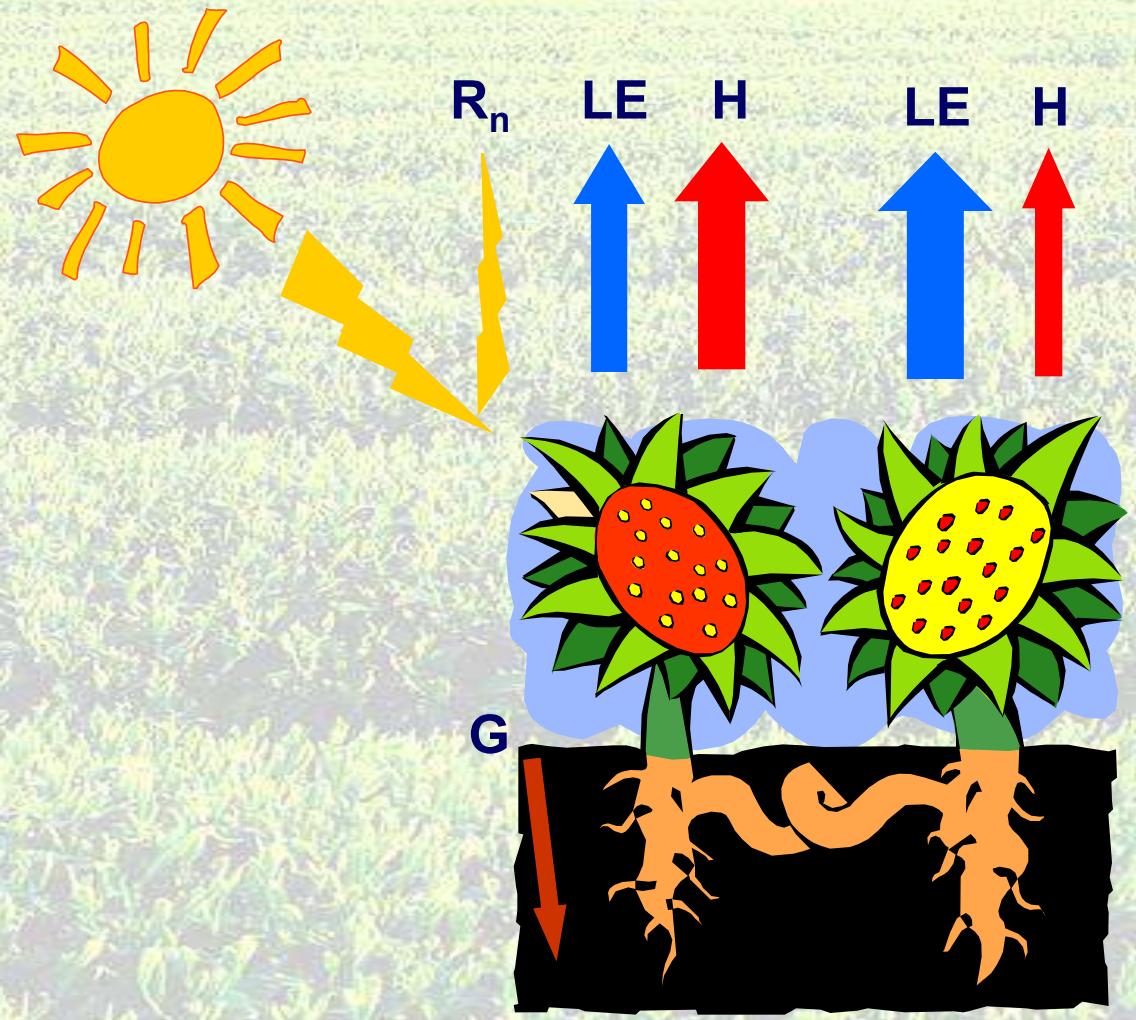
Energy balance

$$R_n = LE + H + G$$

$$\lambda E_s = \frac{s(R_n - G) + \rho_a c_p VPD / r_a}{s + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

$$H = \rho c_p \frac{T_s - T_r}{r_a^H}$$

Energy balance



Energy balance

$R_n = LE + H + G$

$gs_{red} < gs_{yellow}$

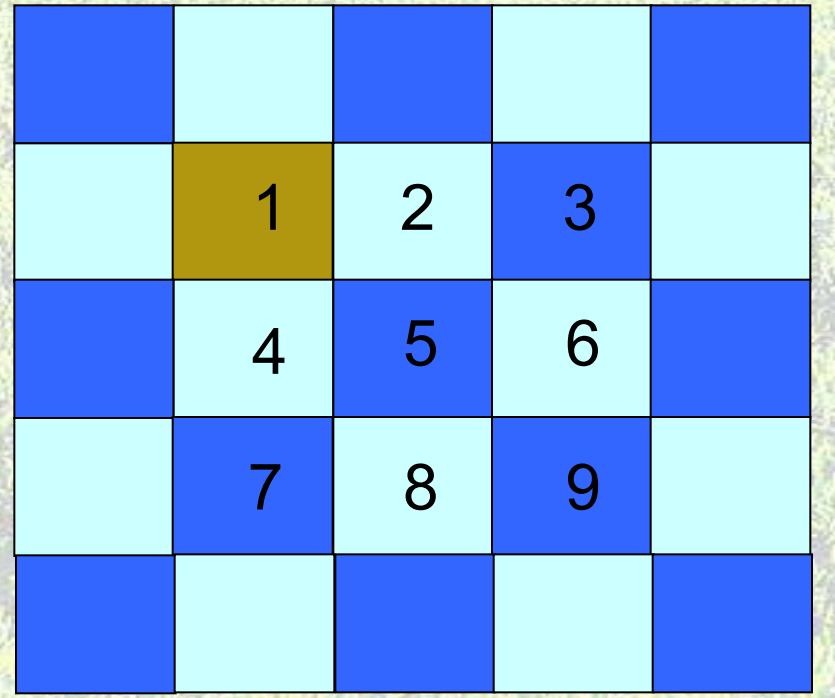
$T_{red} > T_{yellow}$

Energy balance



Energy balance

Two irrigation treatments

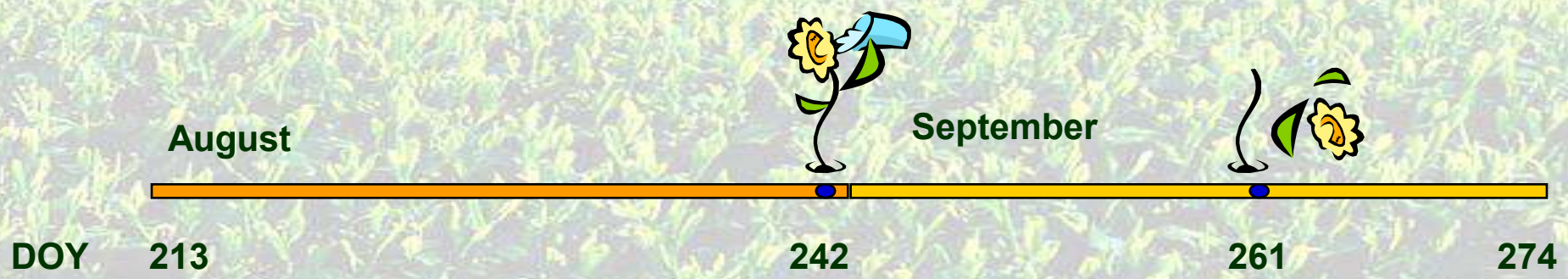


: bare soil
: low irrigation
: high irrigation

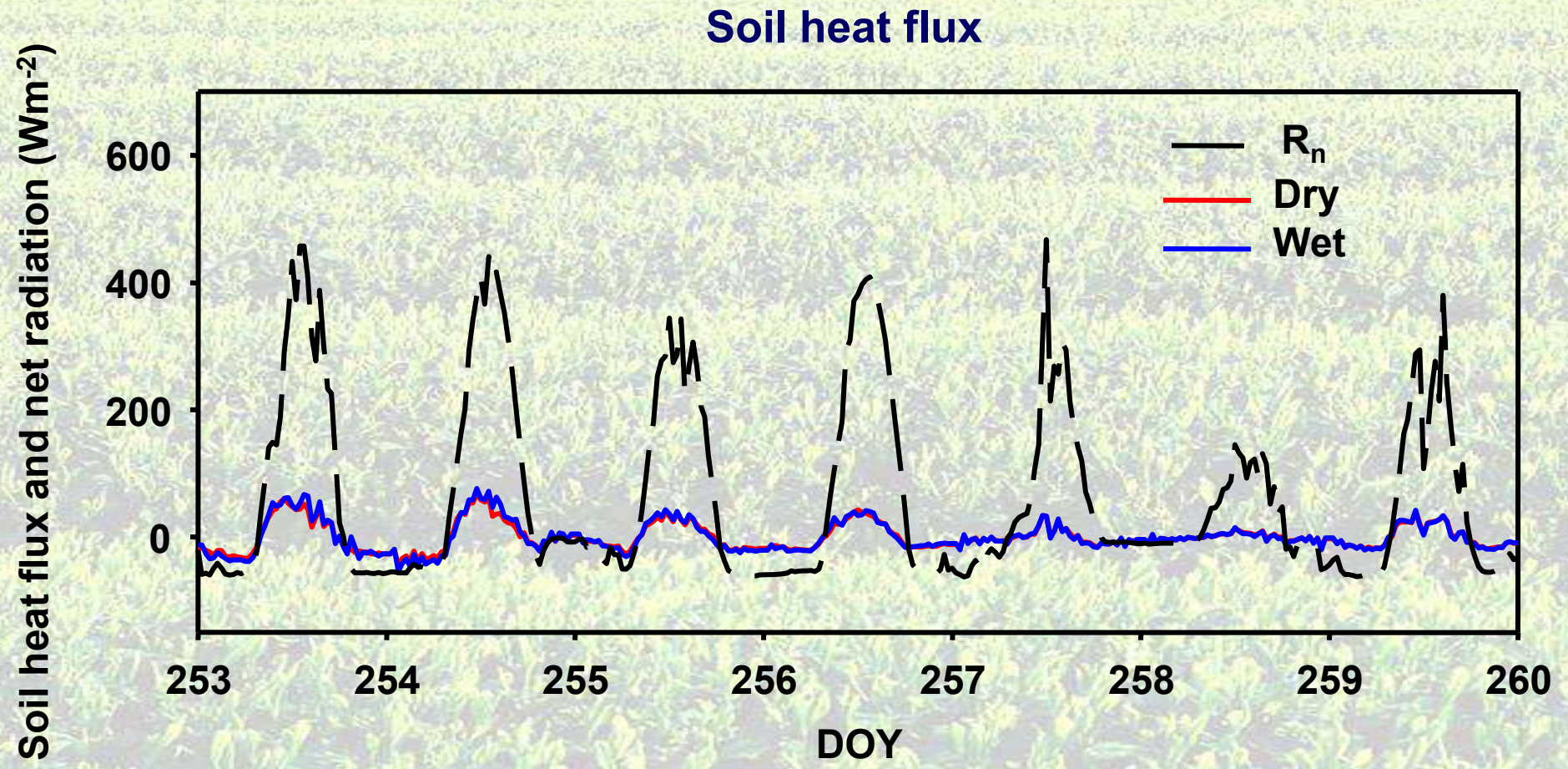
Differences in irrigaiton (liters)

Whole experiment: 70 %

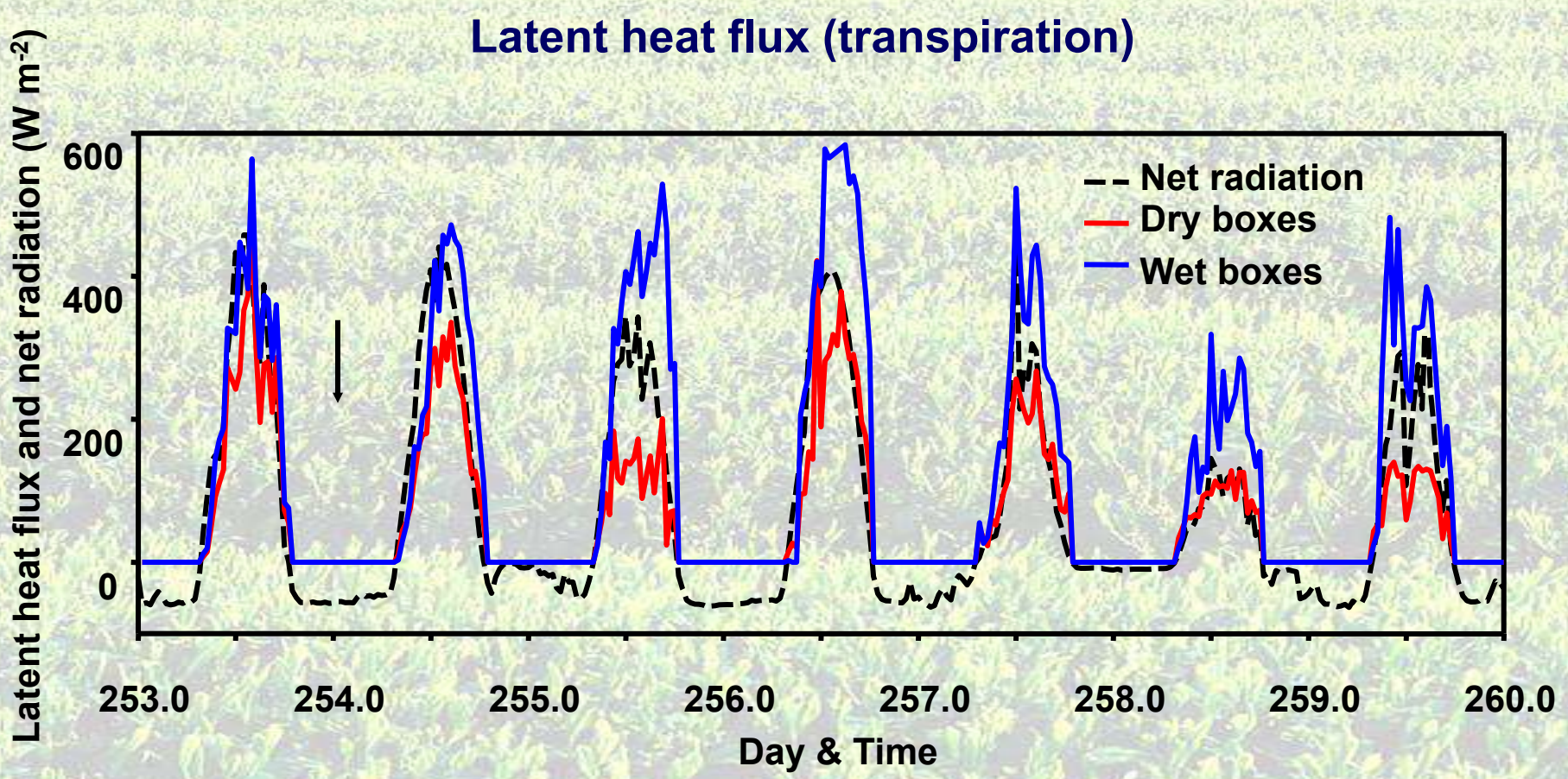
From DOY 242: 60 %



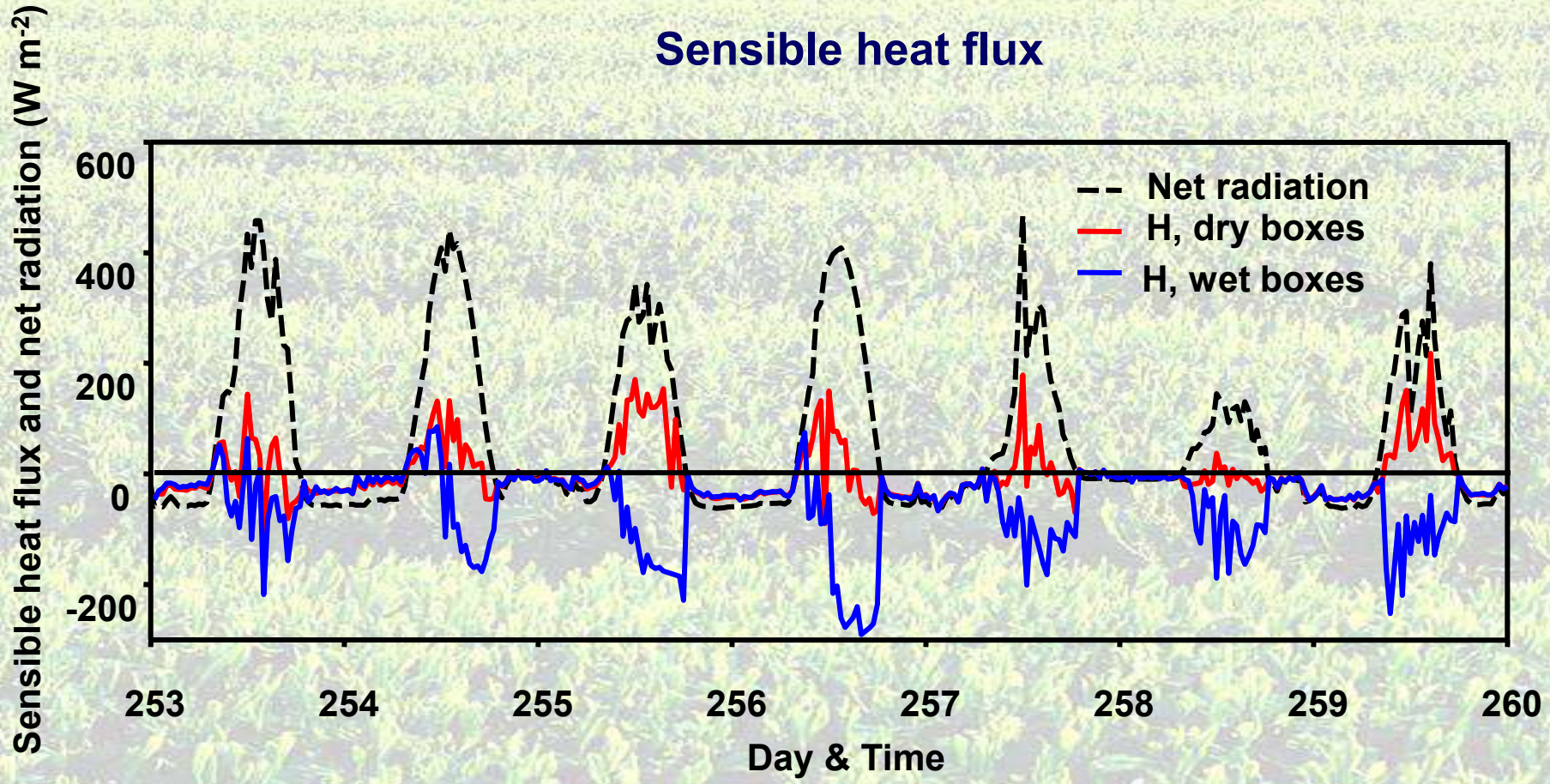
Energy balance



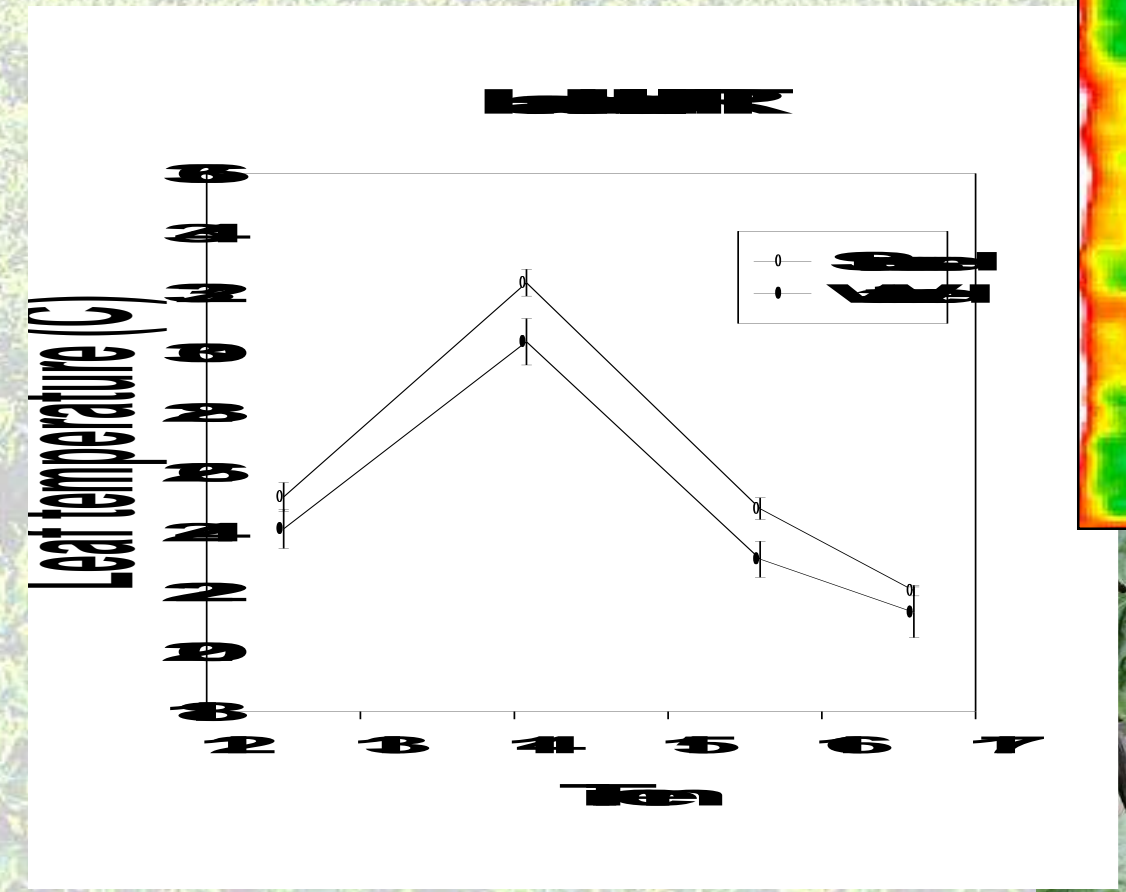
Energy balance

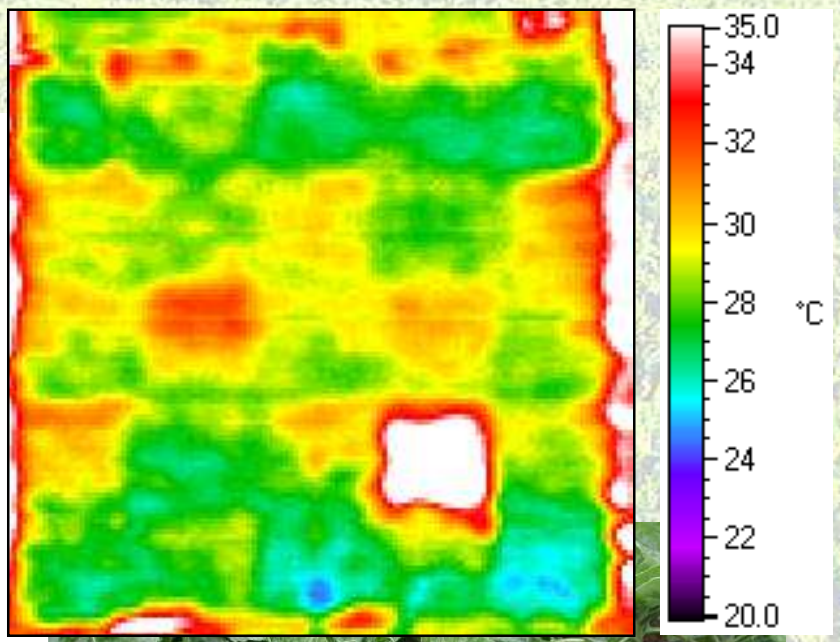


Energy balance



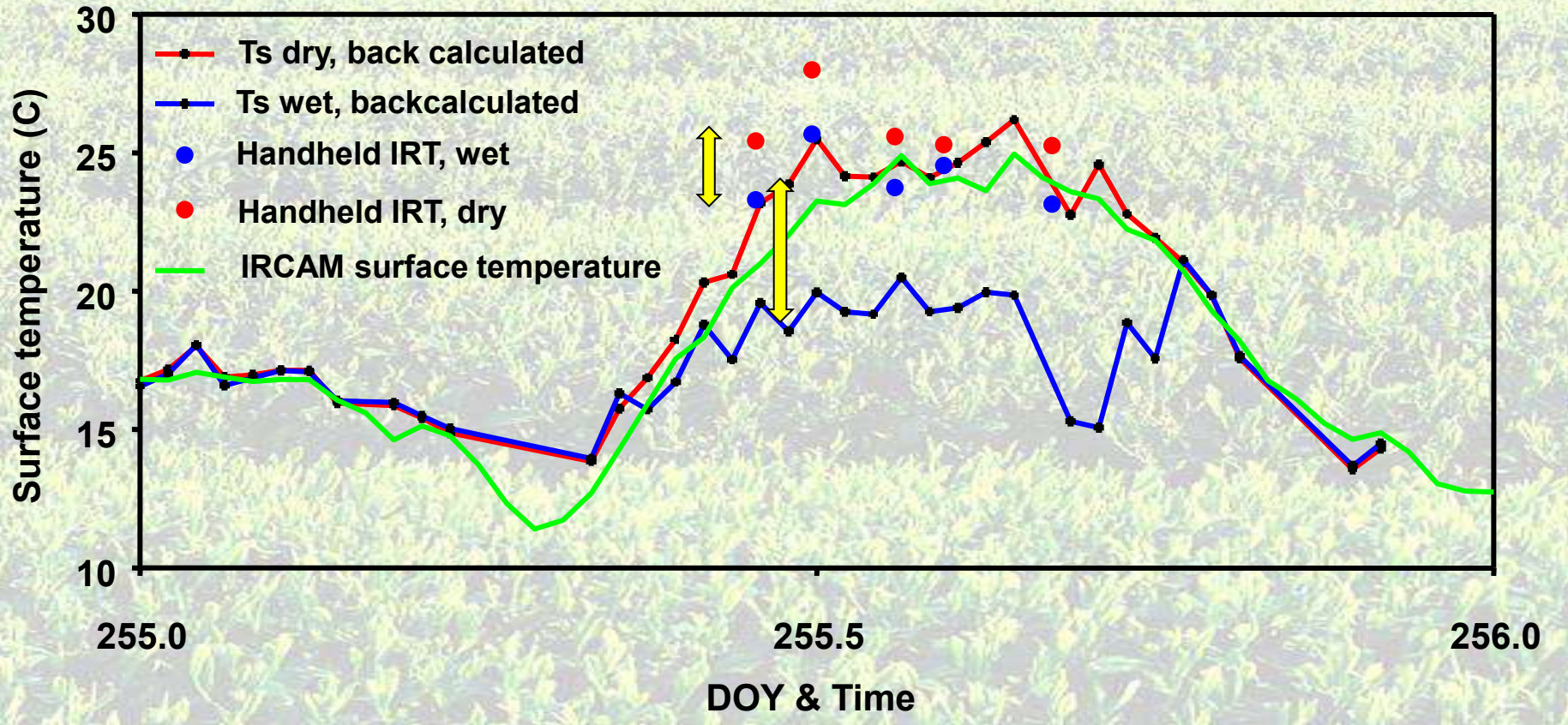
Energy balance



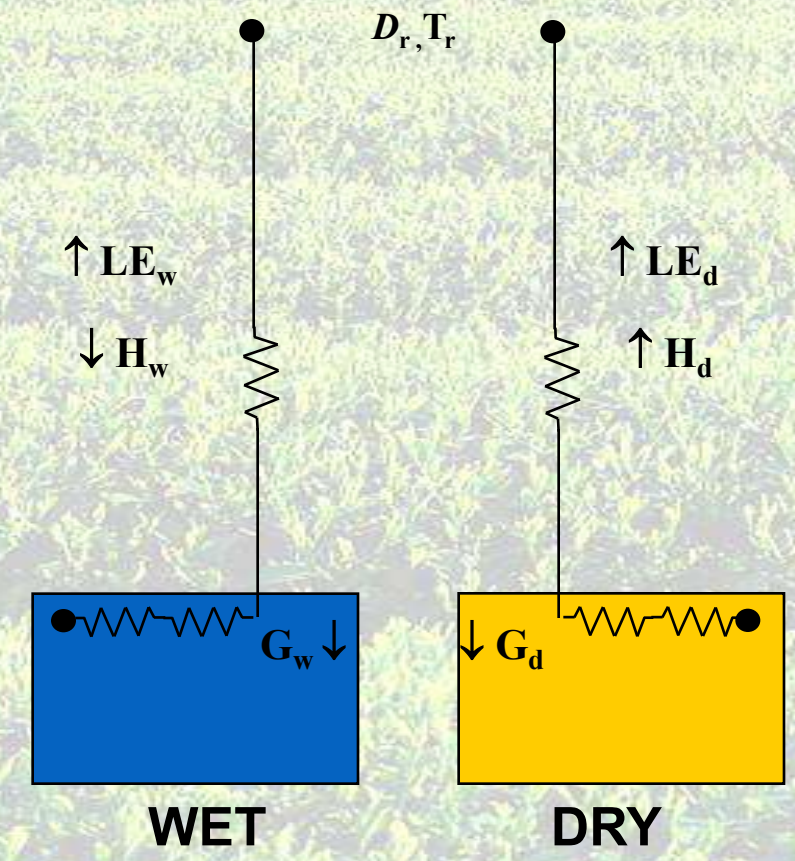




Energy balance



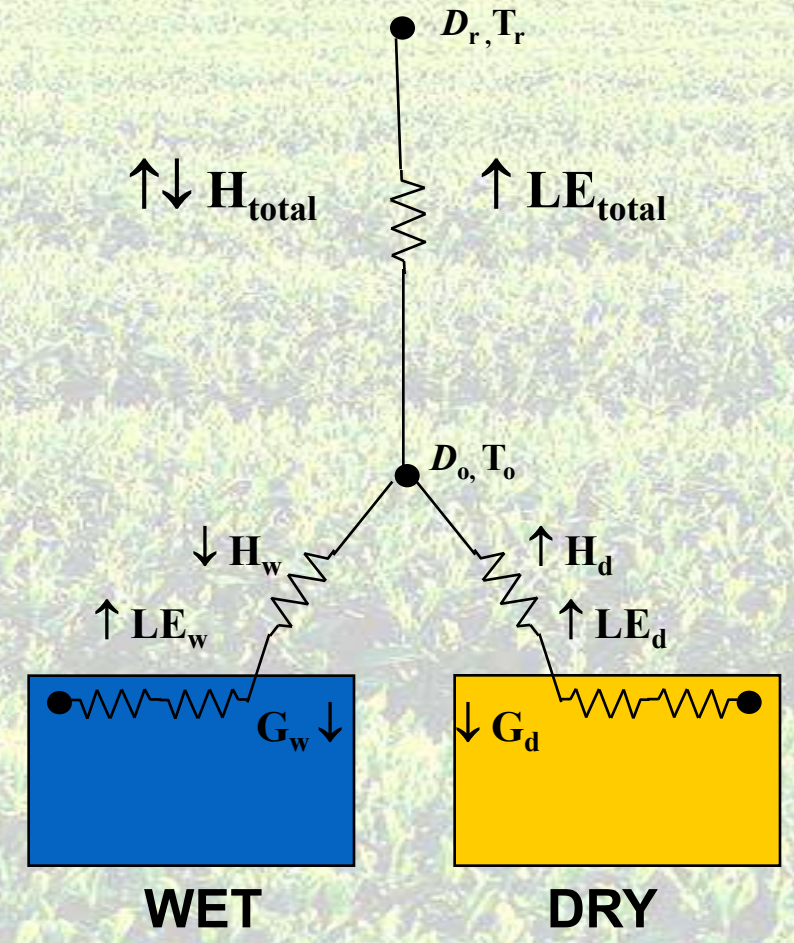
Energy balance



Tile model

$$H = \rho c_p \frac{T_s - T_r}{r_a^H}$$

Energy balance

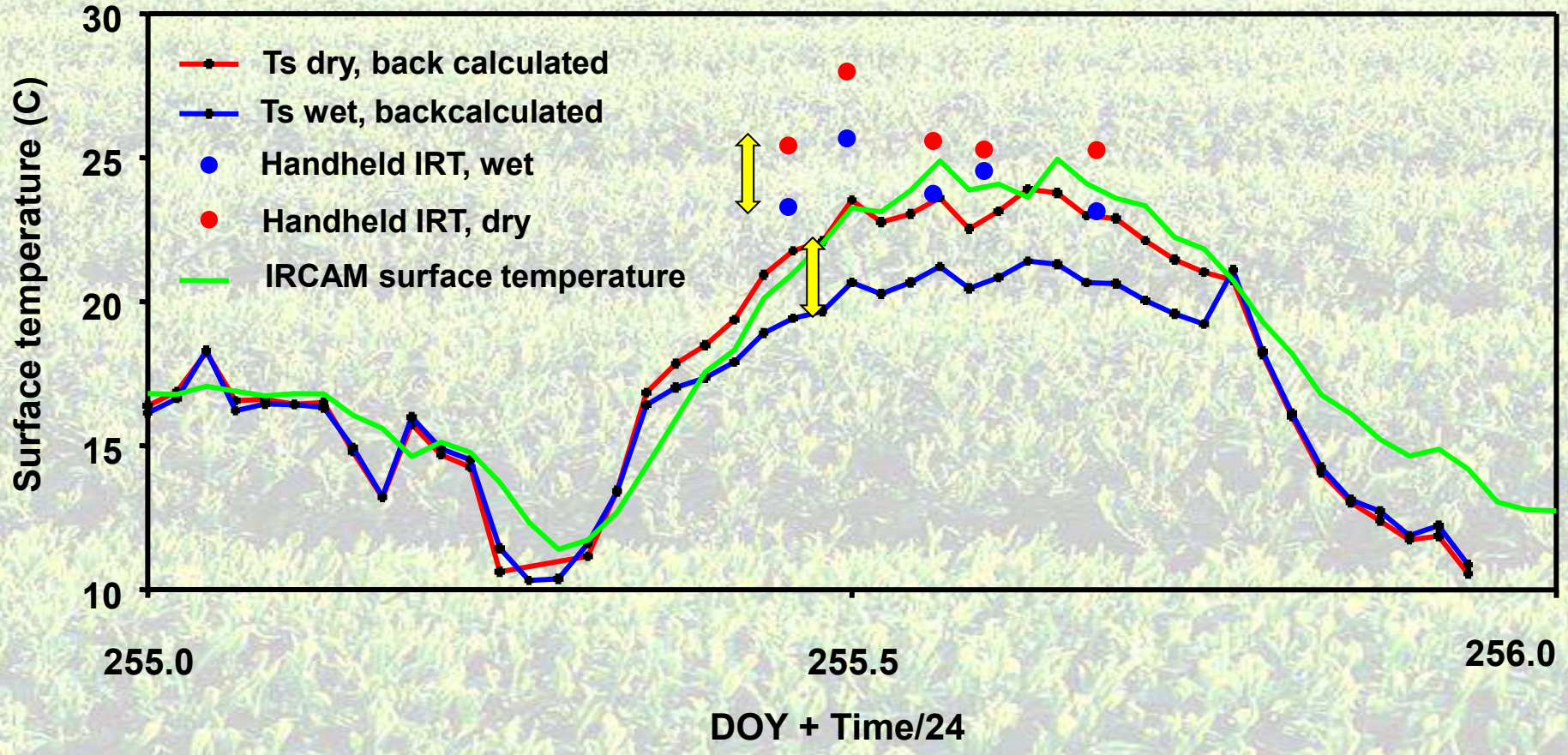


Blending height model

$$H = \rho c_p \frac{T_s - T_o}{r_a^H}$$

(Blyth, 1995)

Energy balance



Mechanims of avoidance of radiation interception

Avoidance mechanisms







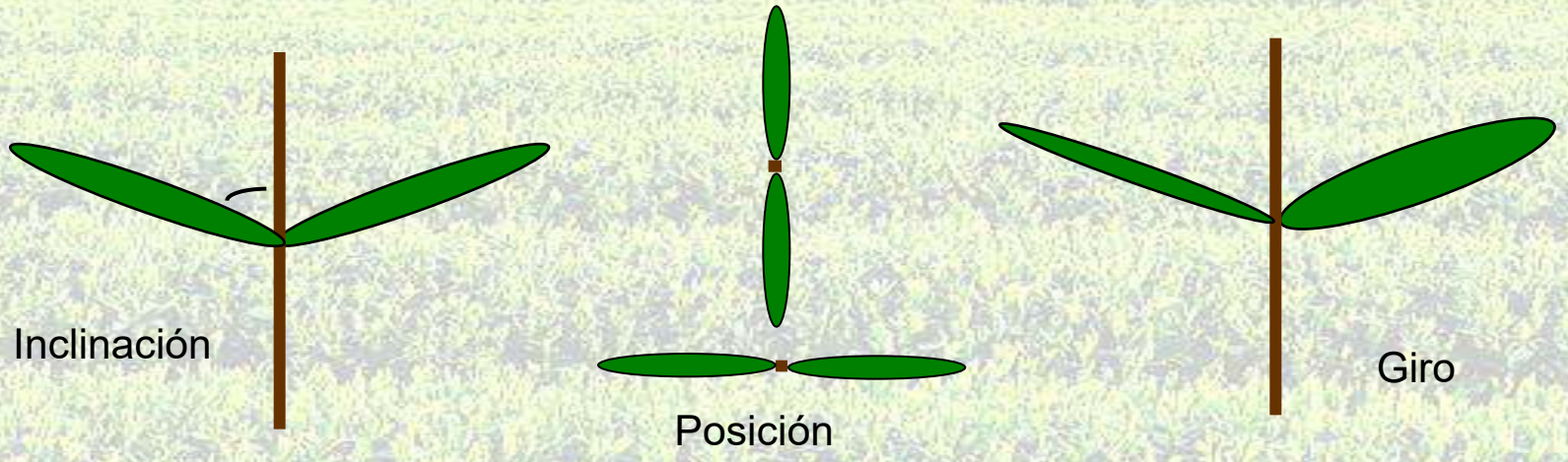
Avoidance mechanisms

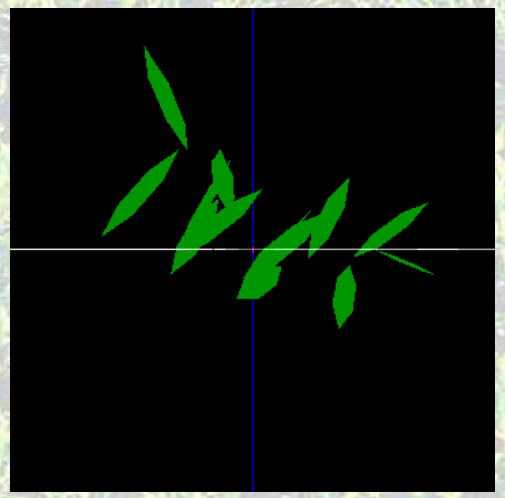




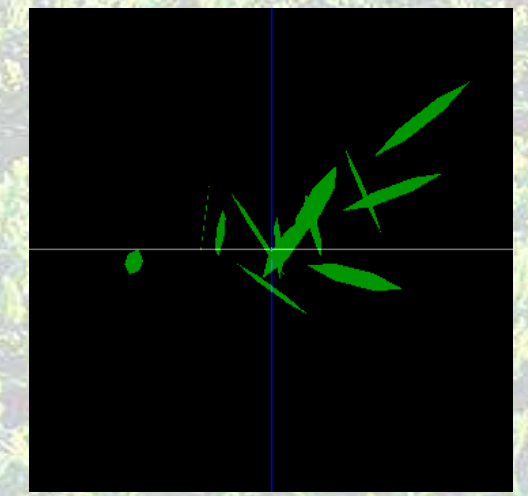
Avoidance mechanisms

Leaf angles

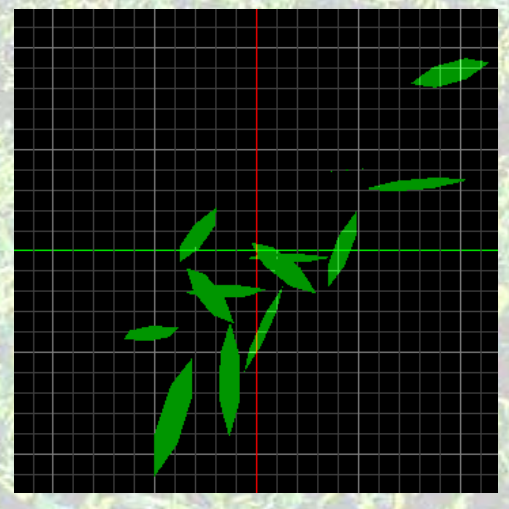




0 azimuth, 0 elevation

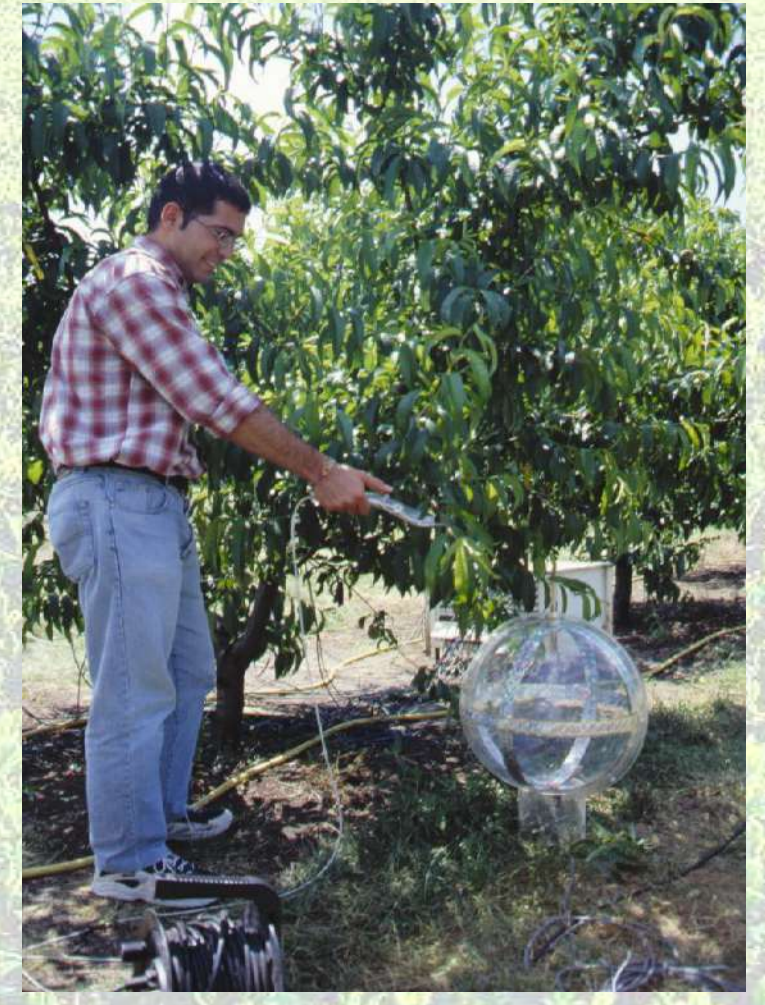


90 azimuth, 0 elevation

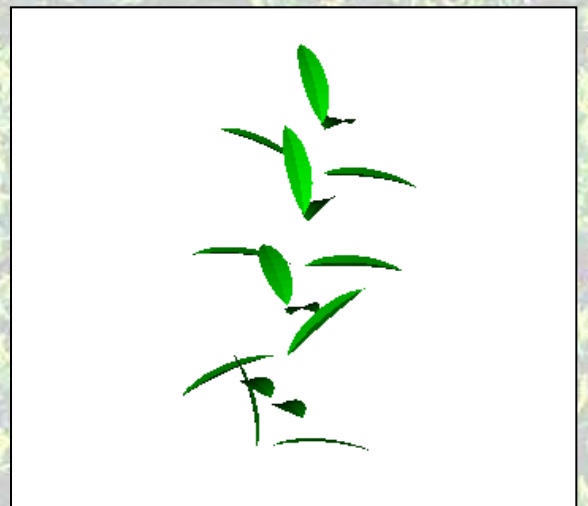


0 azimuth, 90 elevation

Avoidance mechanisms

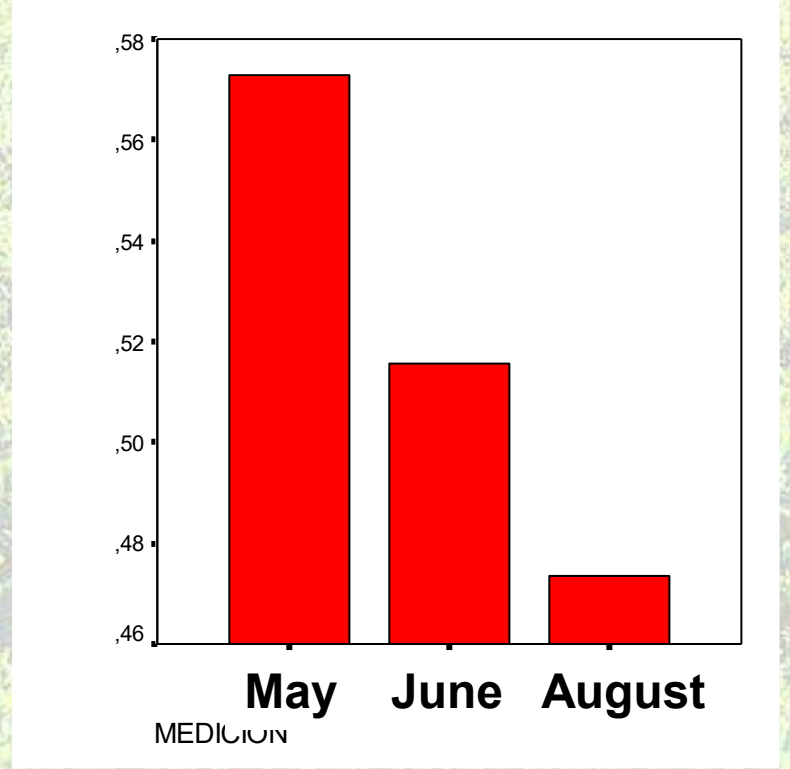




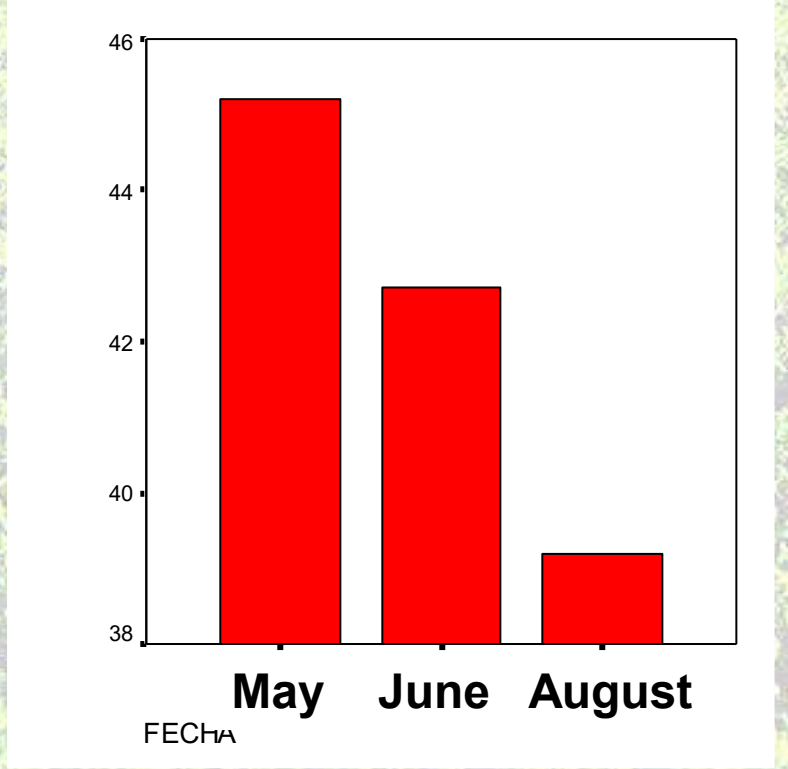


Avoidance mechanisms

Average projected area

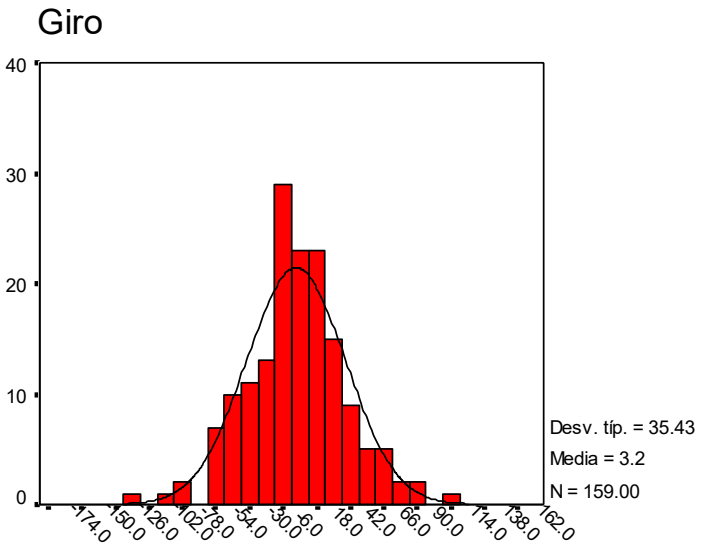


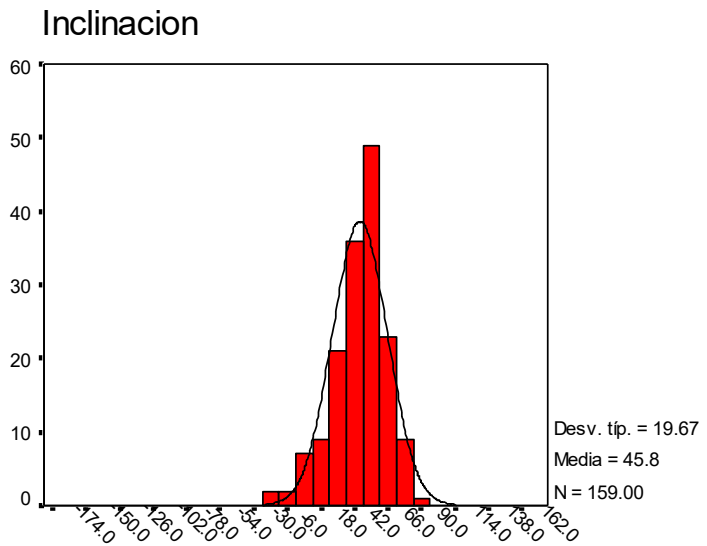
Average leaf angle

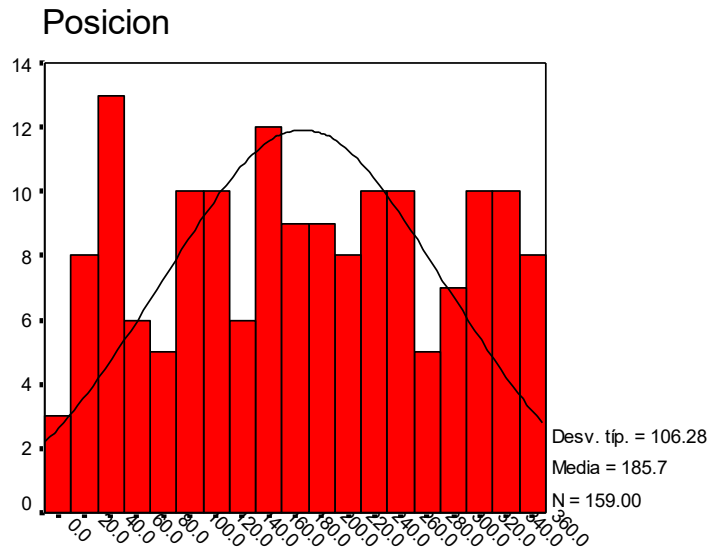




Avoidance mechanisms

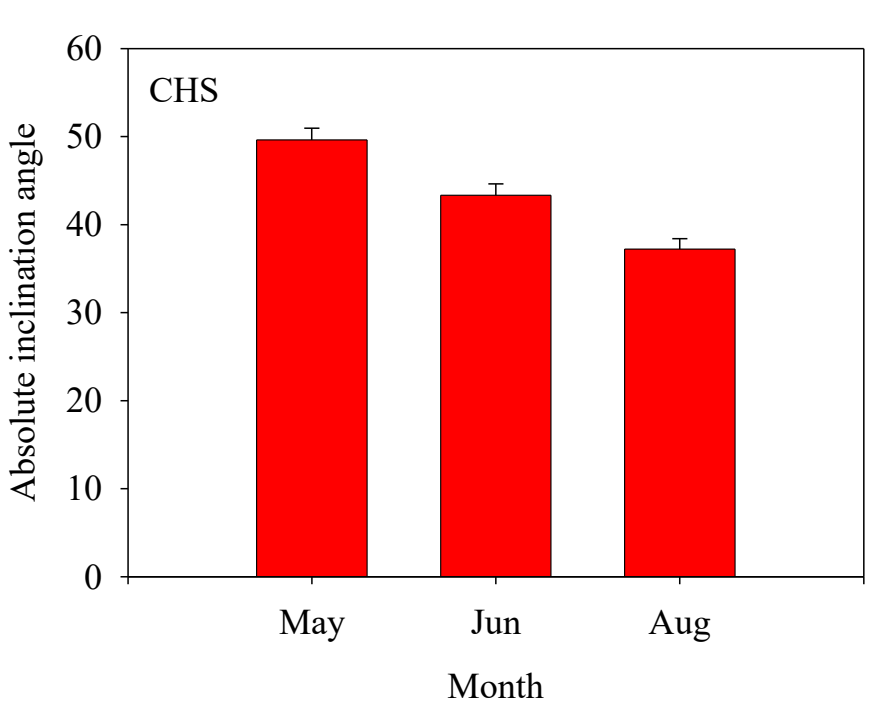




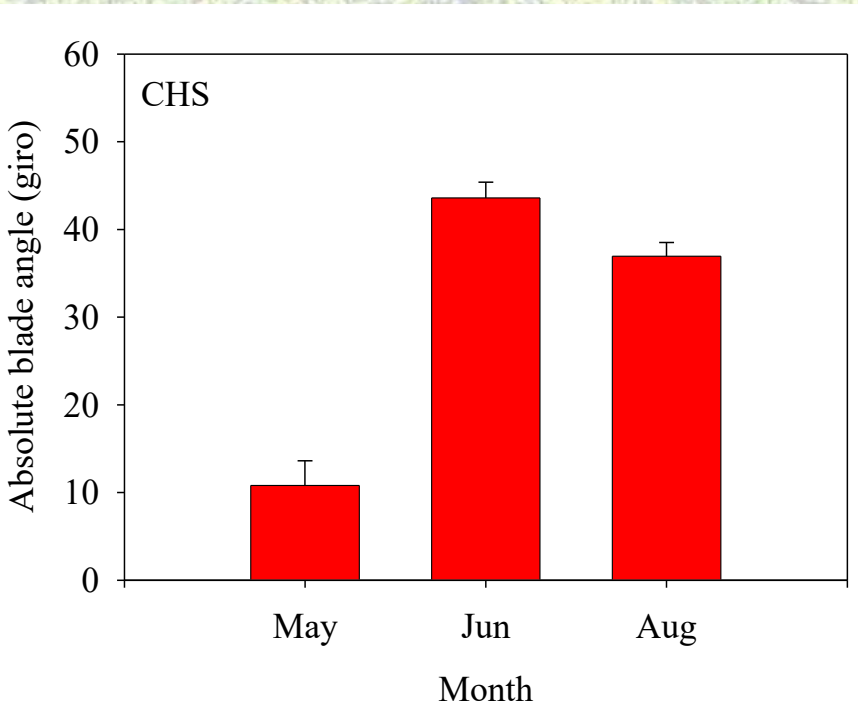


Avoidance mechanisms

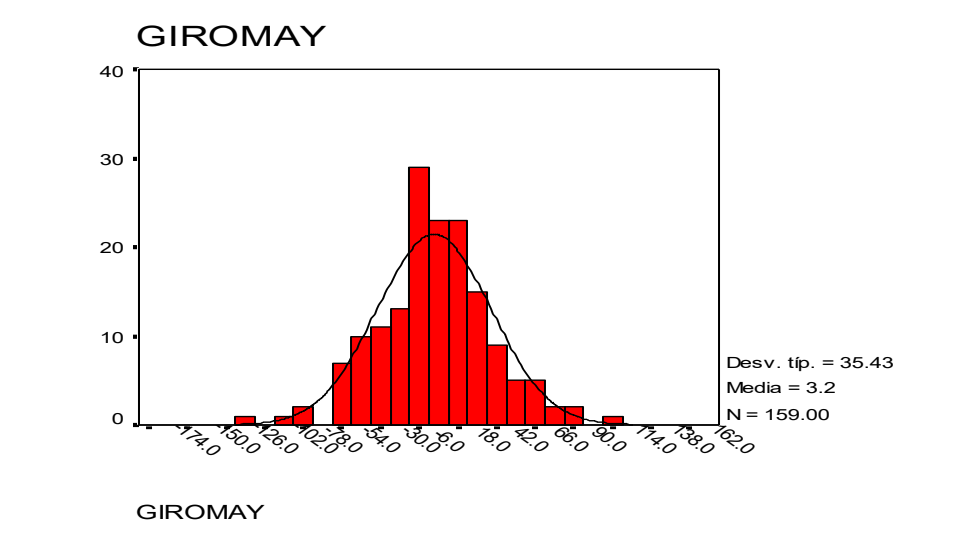
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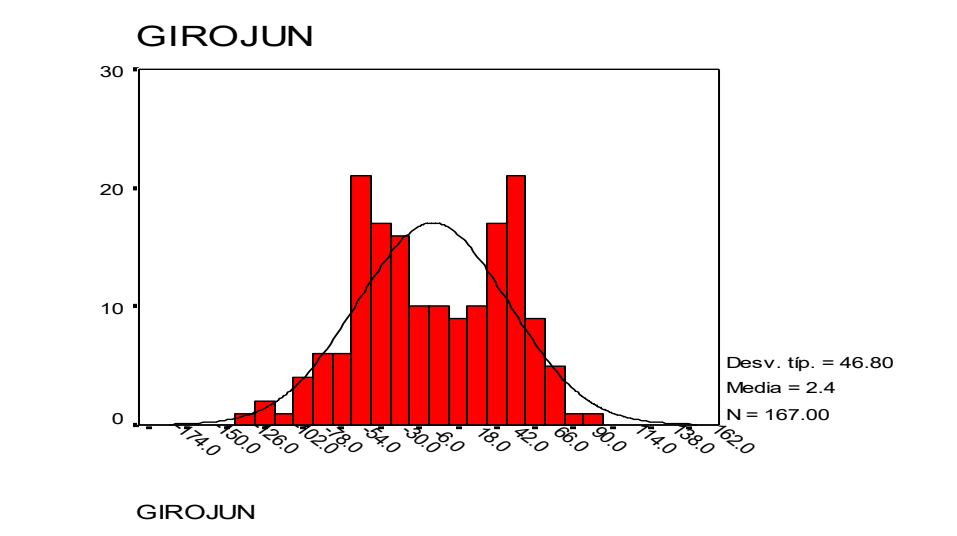


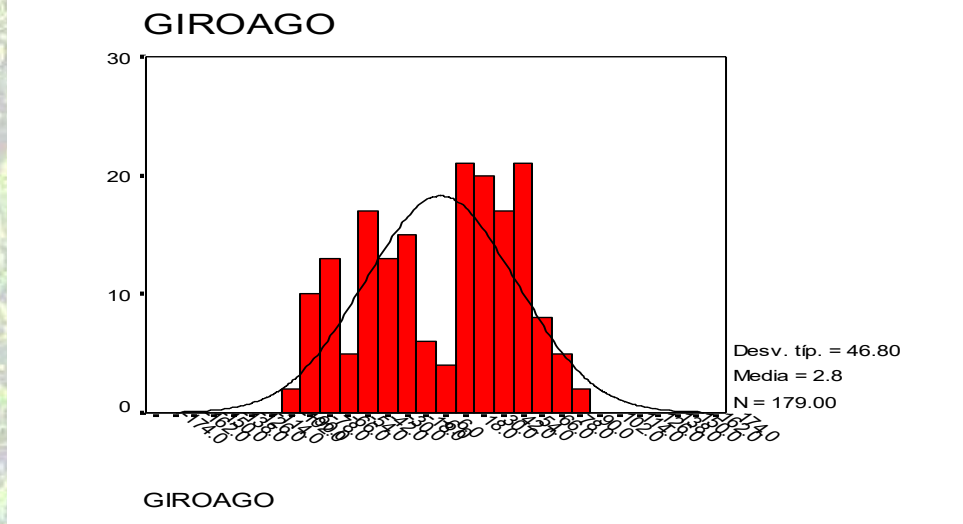
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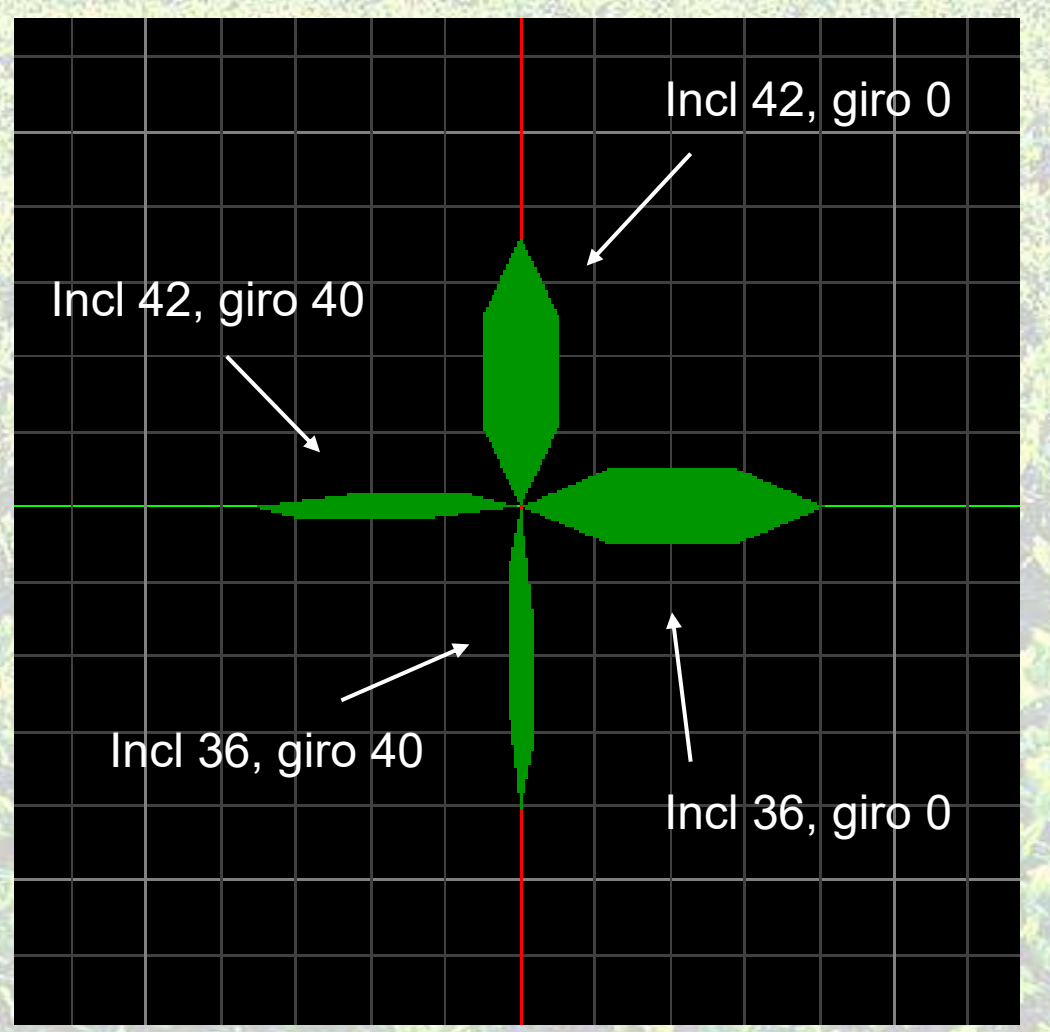
Avoidance mechanisms





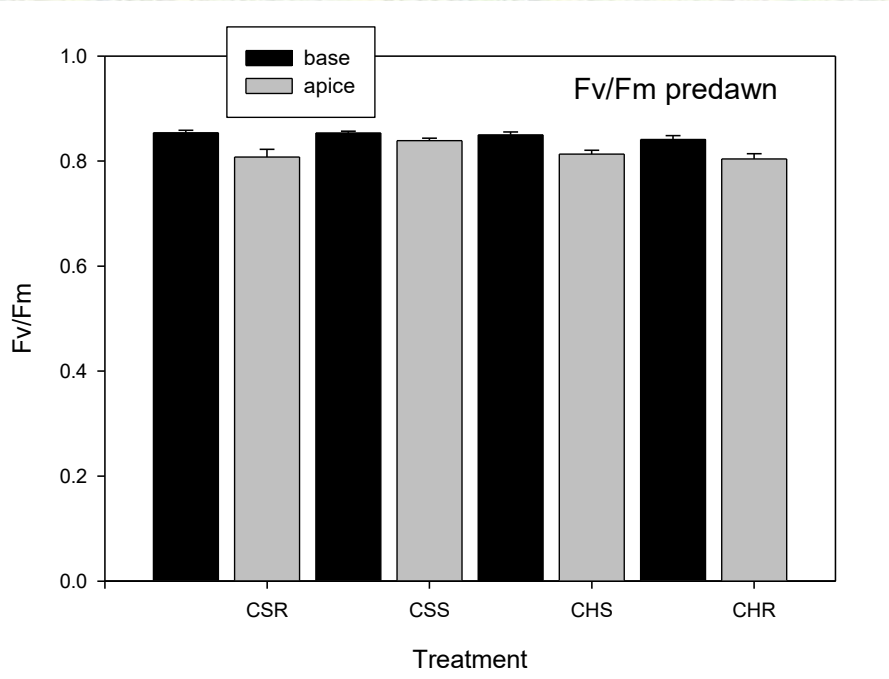


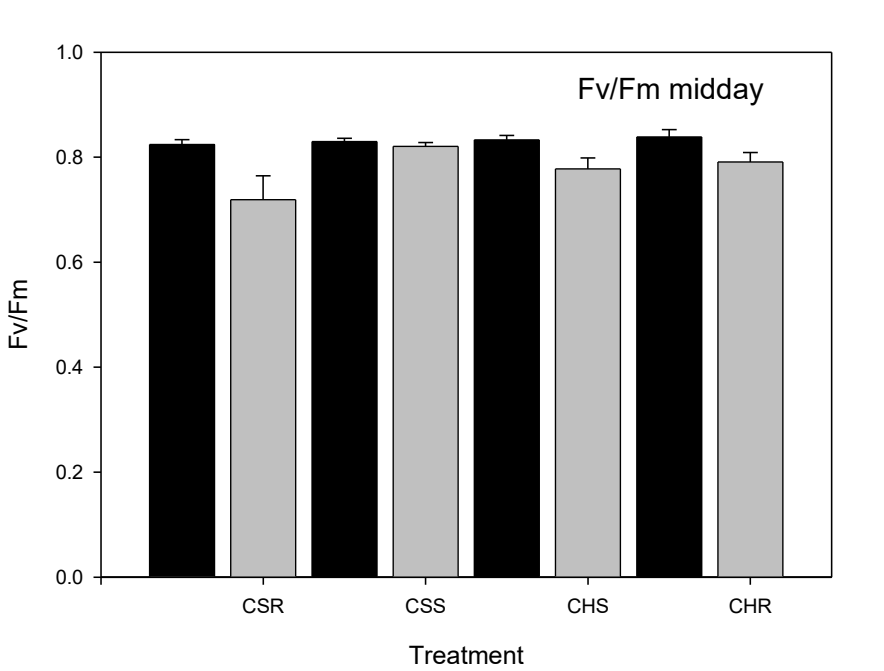
Avoidance mechanisms



Avoidance mechanisms

La integridad del sistema fotosintético se mantiene

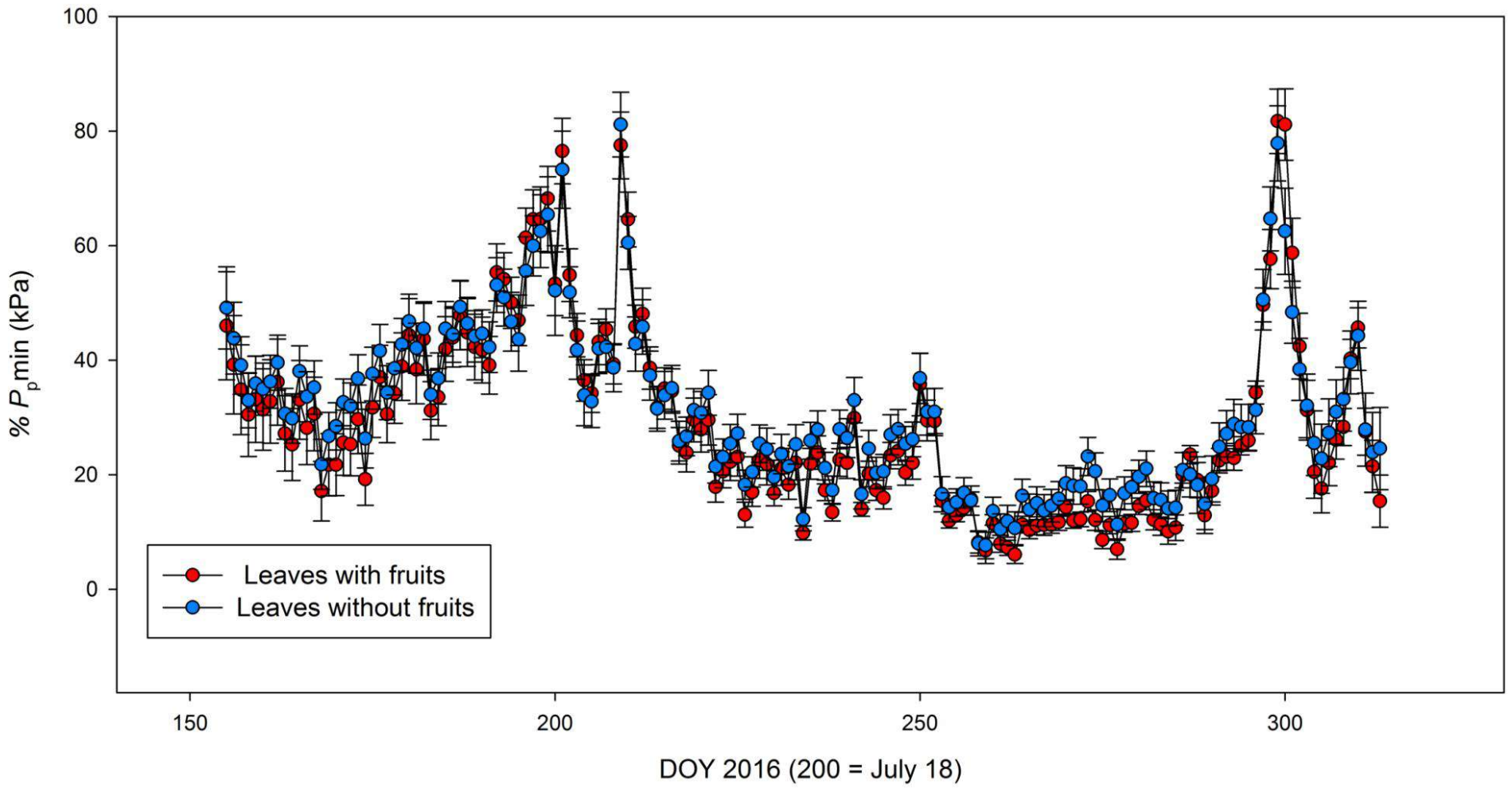




Practical case

“Playing” with the energy balance

Practical case

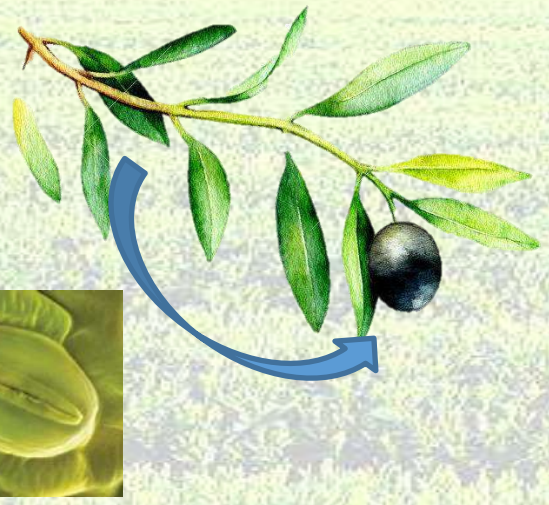


4. Dual effect of fruits on leaf gas exchange and water relations

Published as: **Perez-Arcoiza A**, Diaz-Espejo A, Fernandez-Torres R, Perez-Romero LF, Hernandez-Santana V (2023) *Dual effect of the presence of fruits on leaf gas exchange and water relations of olive trees*. Tree Physiol 43:277–287.



4. Effect of the presence of fruits on leaf gas exchange

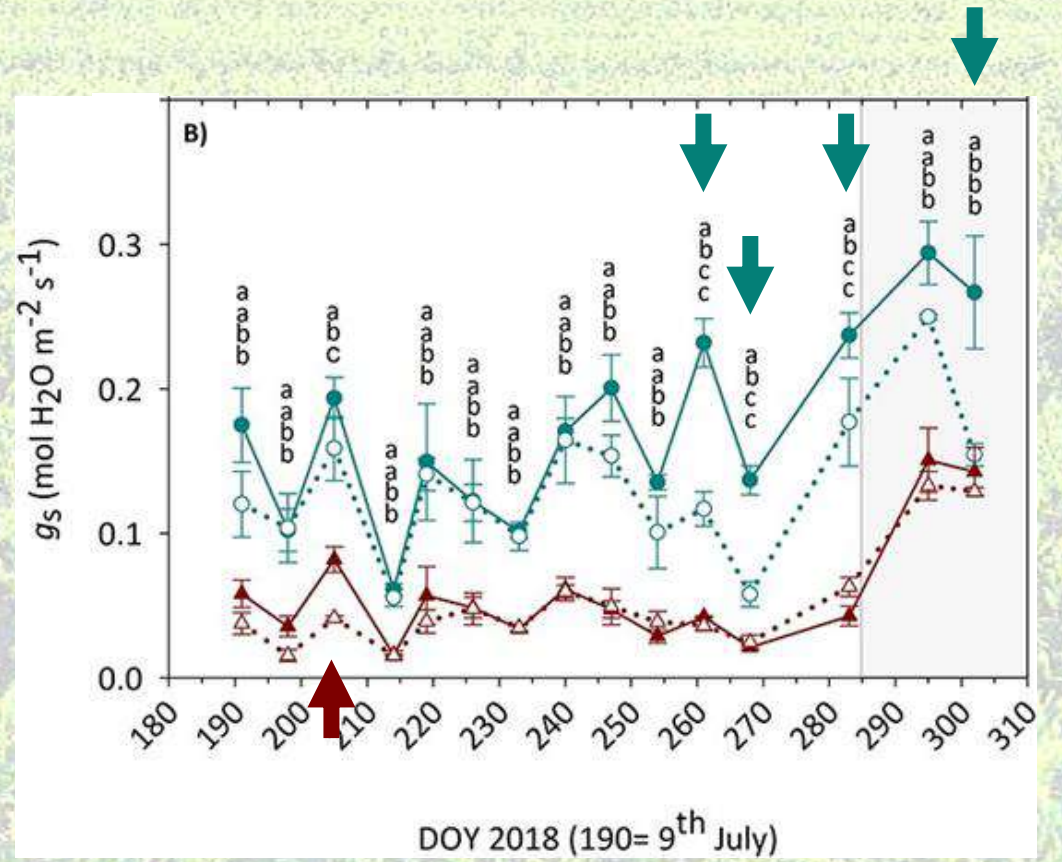


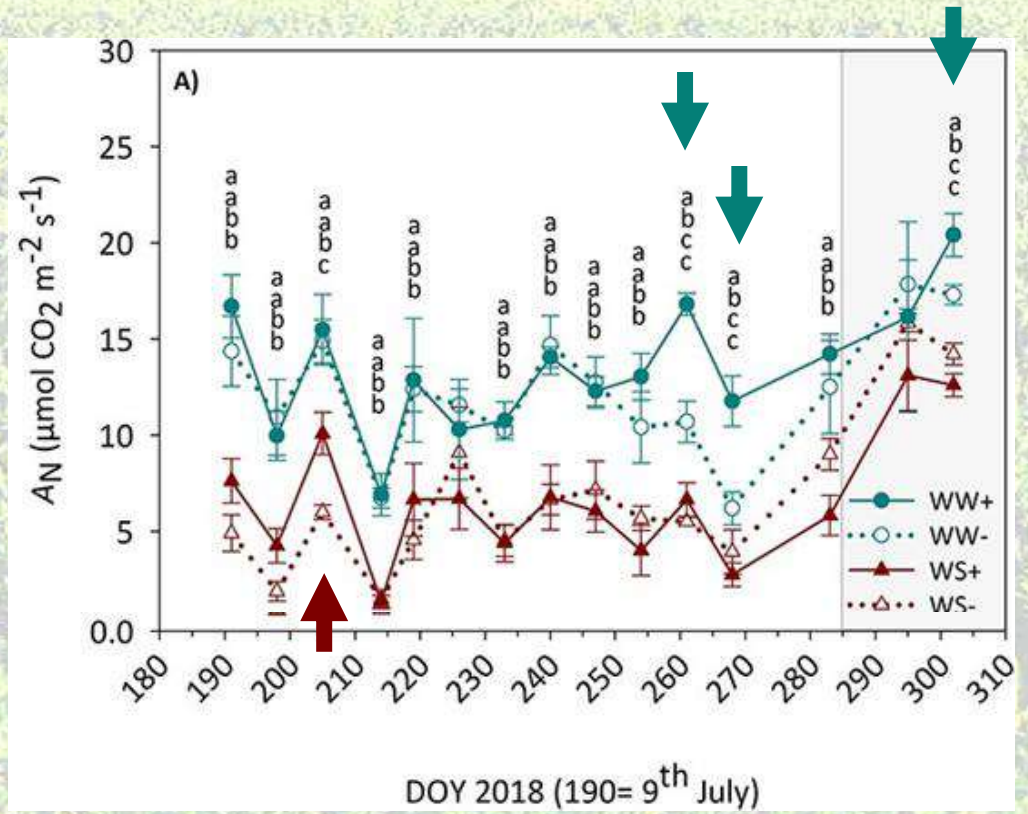


- The presence of fruits increases the export of sugars from leaves, avoiding the inhibition of photosynthesis by end-products and, hence, enhancing the stomata opening

- Furthermore, this effect should be reflected in the leaf water relations, and, particularly, in the turgor of the leaves.

4. Dual effect of fruits on leaf gas exchange and water relations

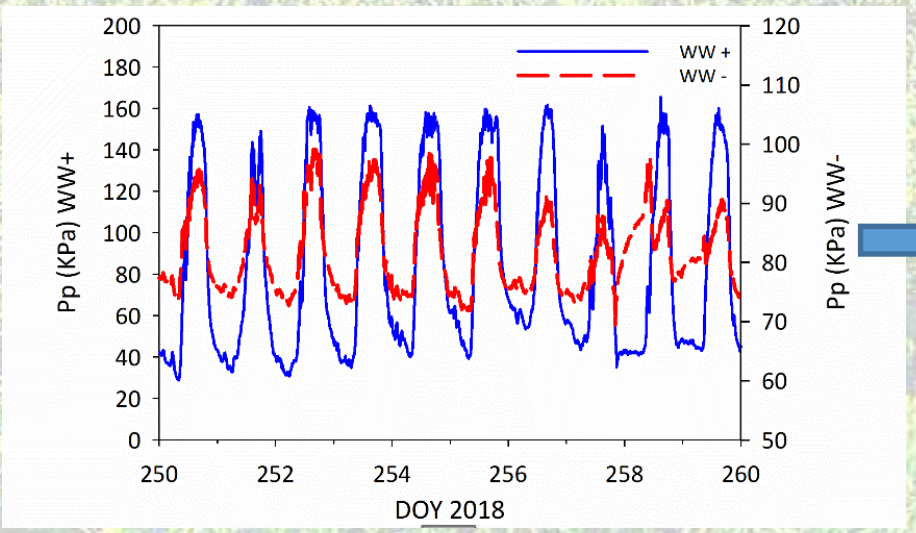


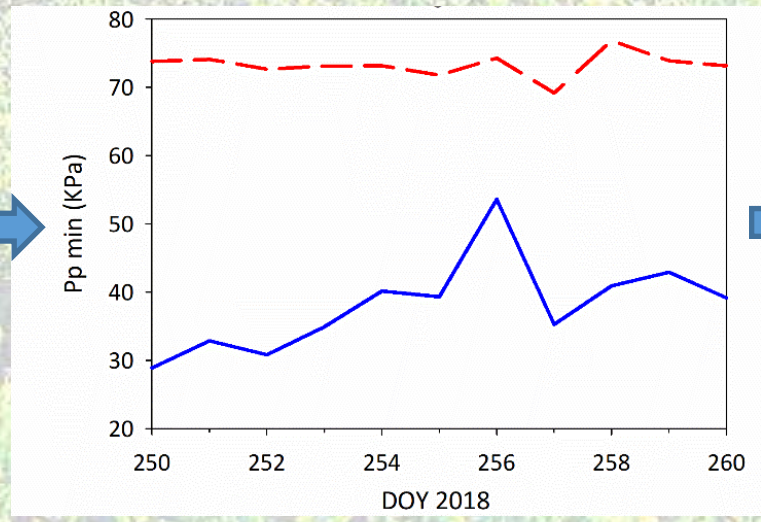


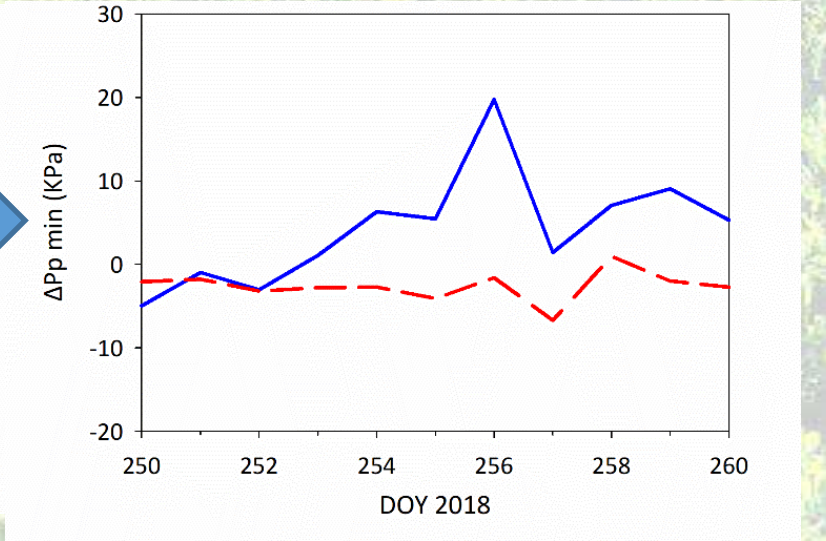
4. Dual effect of fruits on leaf gas exchange and water relations



Leaf turgor measurements can detect when leaf sugars are demanded and exported

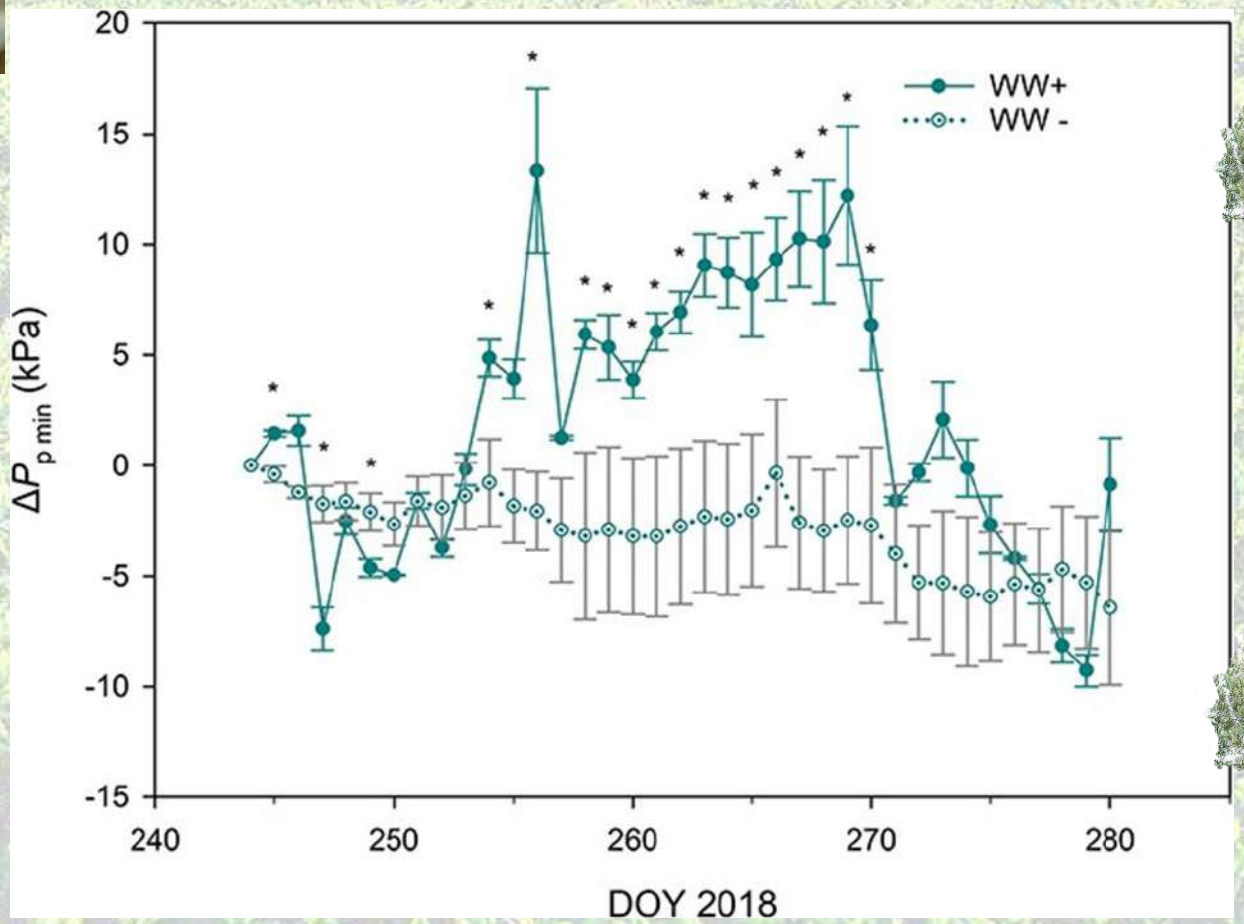


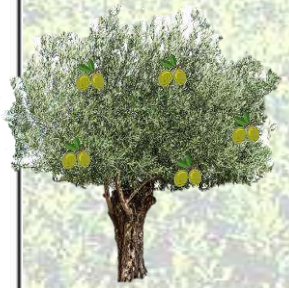




4. Dual effect of fruits on leaf gas exchange and water relations







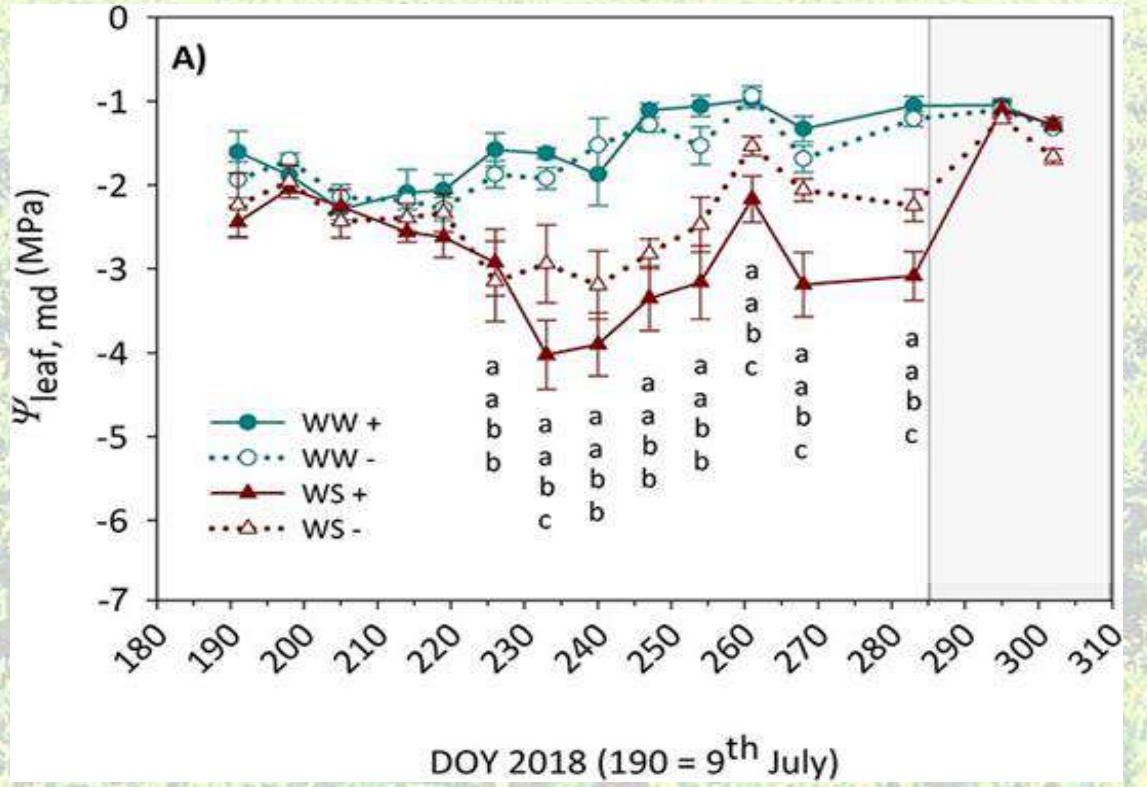
Trees WITH fruits
WW+

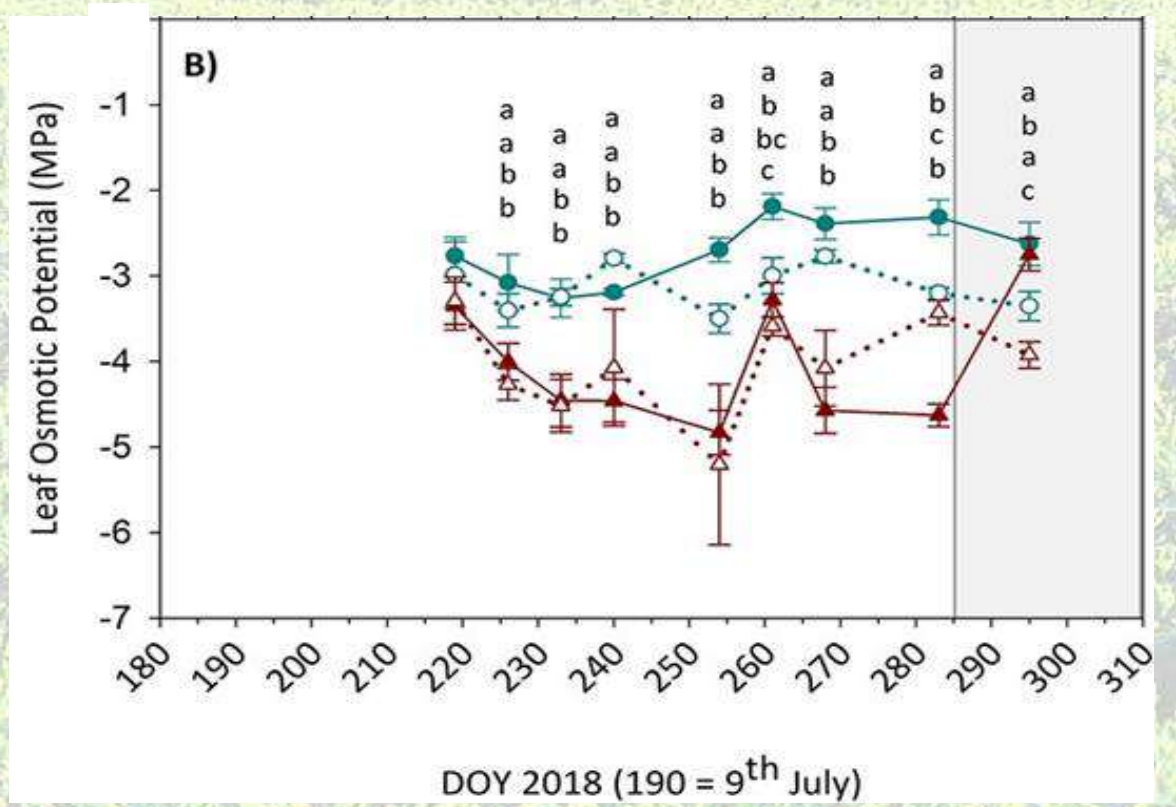


Trees WITHOUT fruits
WW-

4. Dual effect of fruits on leaf gas exchange and water relations

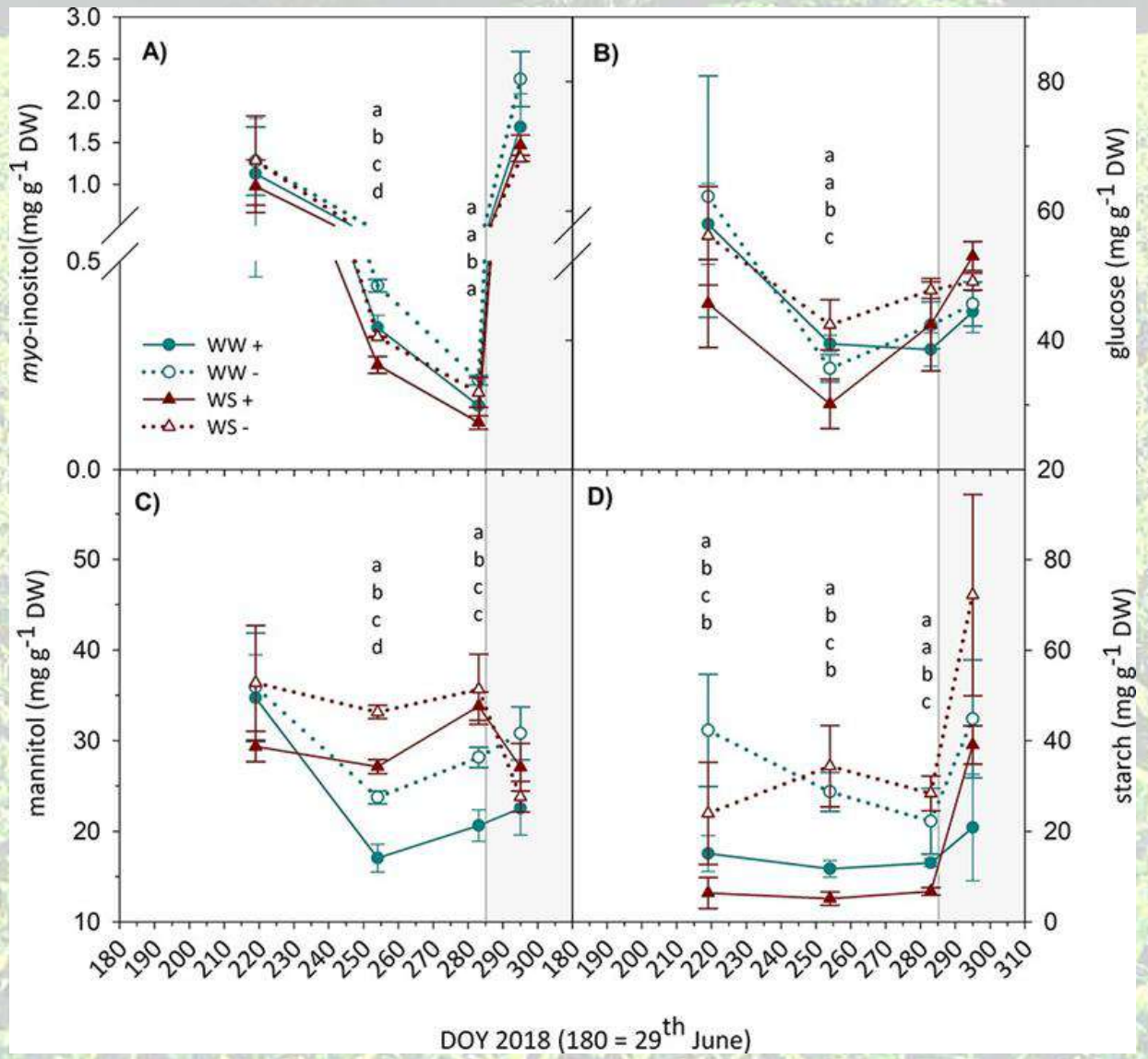
Sink impact on leaf water relations





$$\Psi_{leaf} = \Psi_{\pi} + \Psi_{P}$$

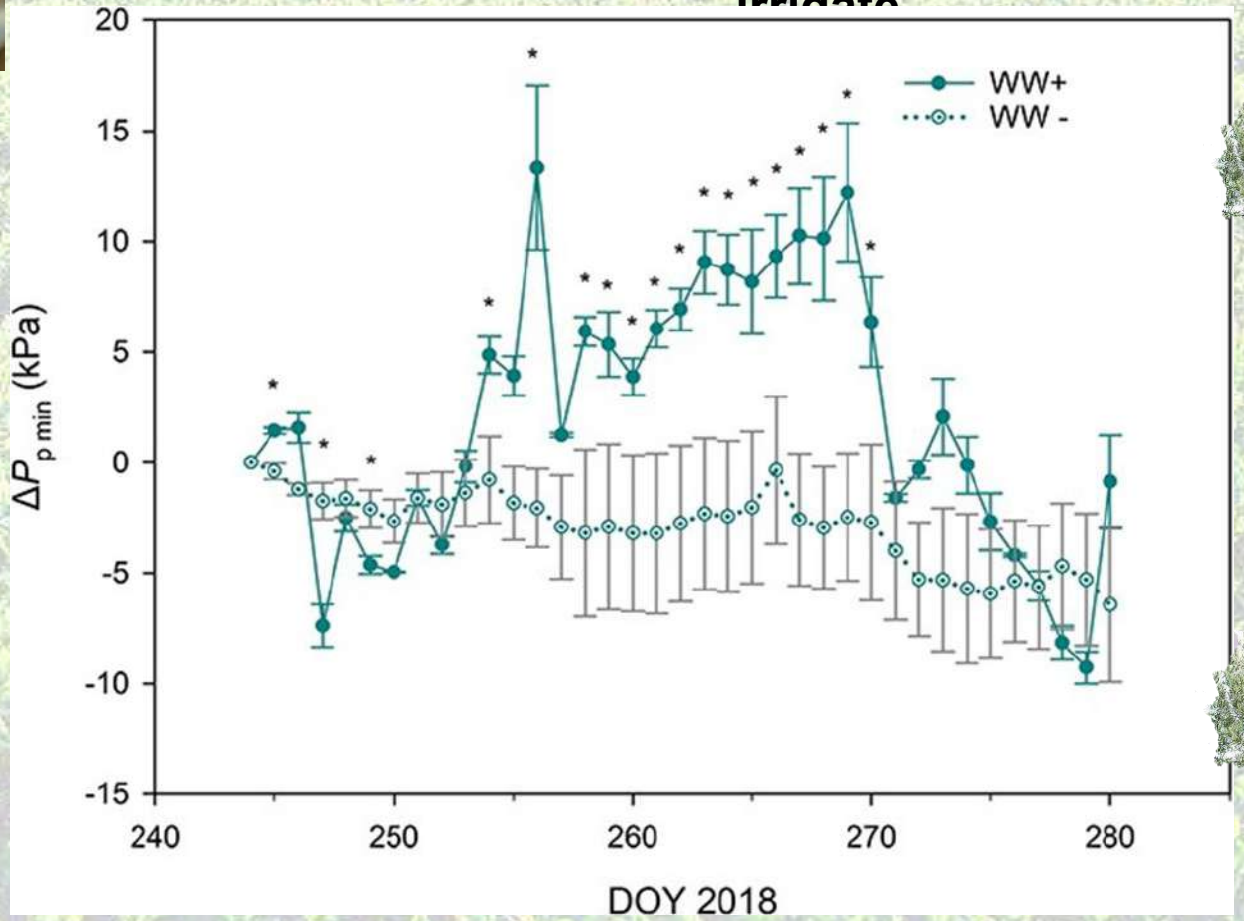
4. Dual effect of fruits on leaf gas exchange and water relations

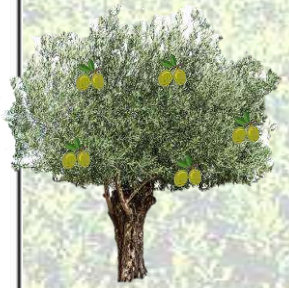


4. Dual effect of fruits on leaf gas exchange and water relations



Leaf turgor measurements can help to choose the best moment to irrigate





Trees WITH fruits
WW+



Trees WITHOUT fruits
WW-



Deficit Irrigation as a Strategic Necessity for Fruit Tree Crops under Intensifying Drought Conditions



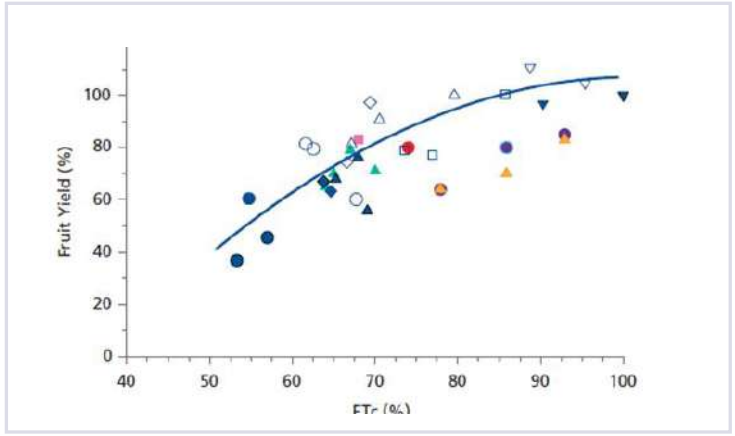


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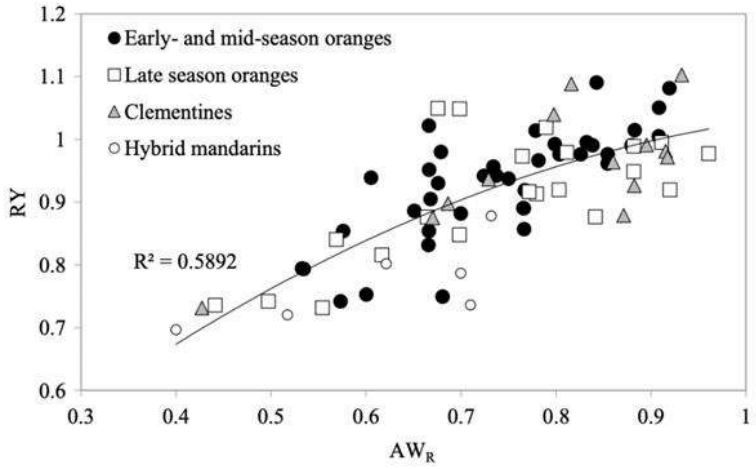
The production curve

OLIVE



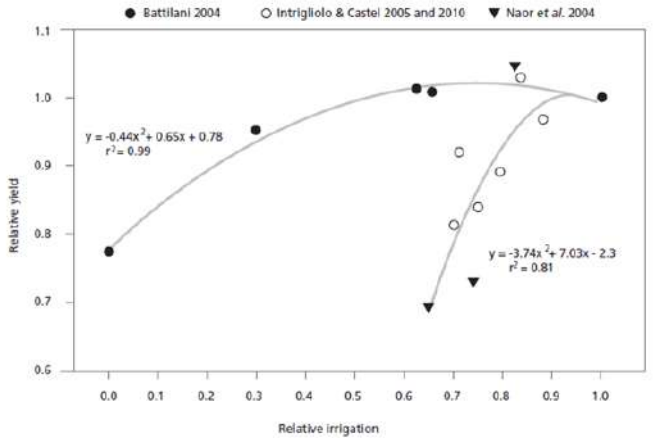
Gucci et al. (2012)

CITRUS



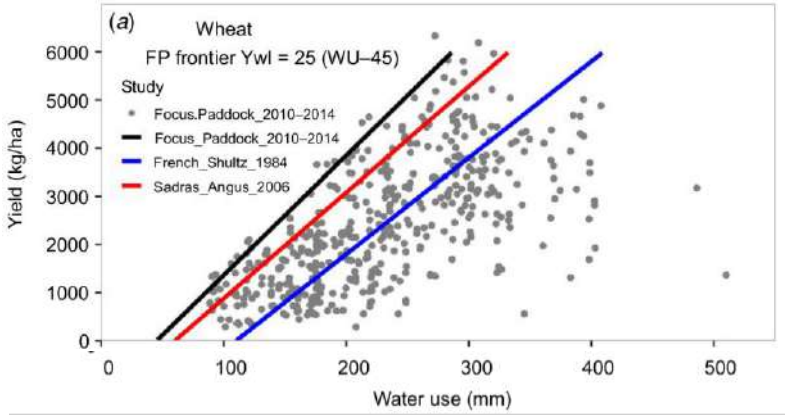
González-Dugo et al. (2018)

PLUM



Intrigliolo et al. (2012)

WHEAT



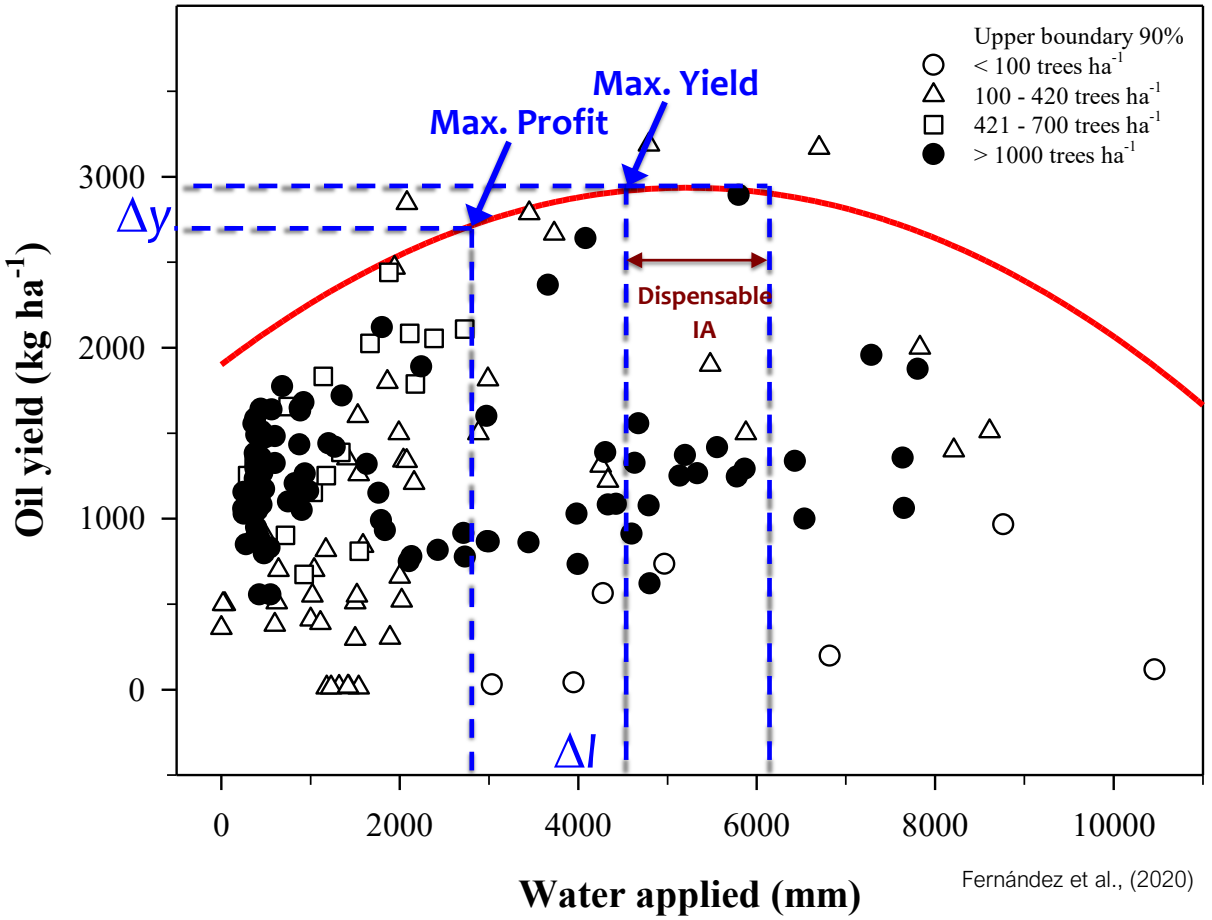
Harries et al. (2022)

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Should we apply deficit irrigation?

Production target = maximum yield

Production target = maximum profit



Fernández et al., (2020)

Maximum profit is achieved by irrigating until null marginal benefit:

To remain below the threshold for the cost of applying ΔI being greater than the market value of Δy.

Barker et al. (2003)

Deficit irrigation may be advisable in crops with curvilinear production curves.

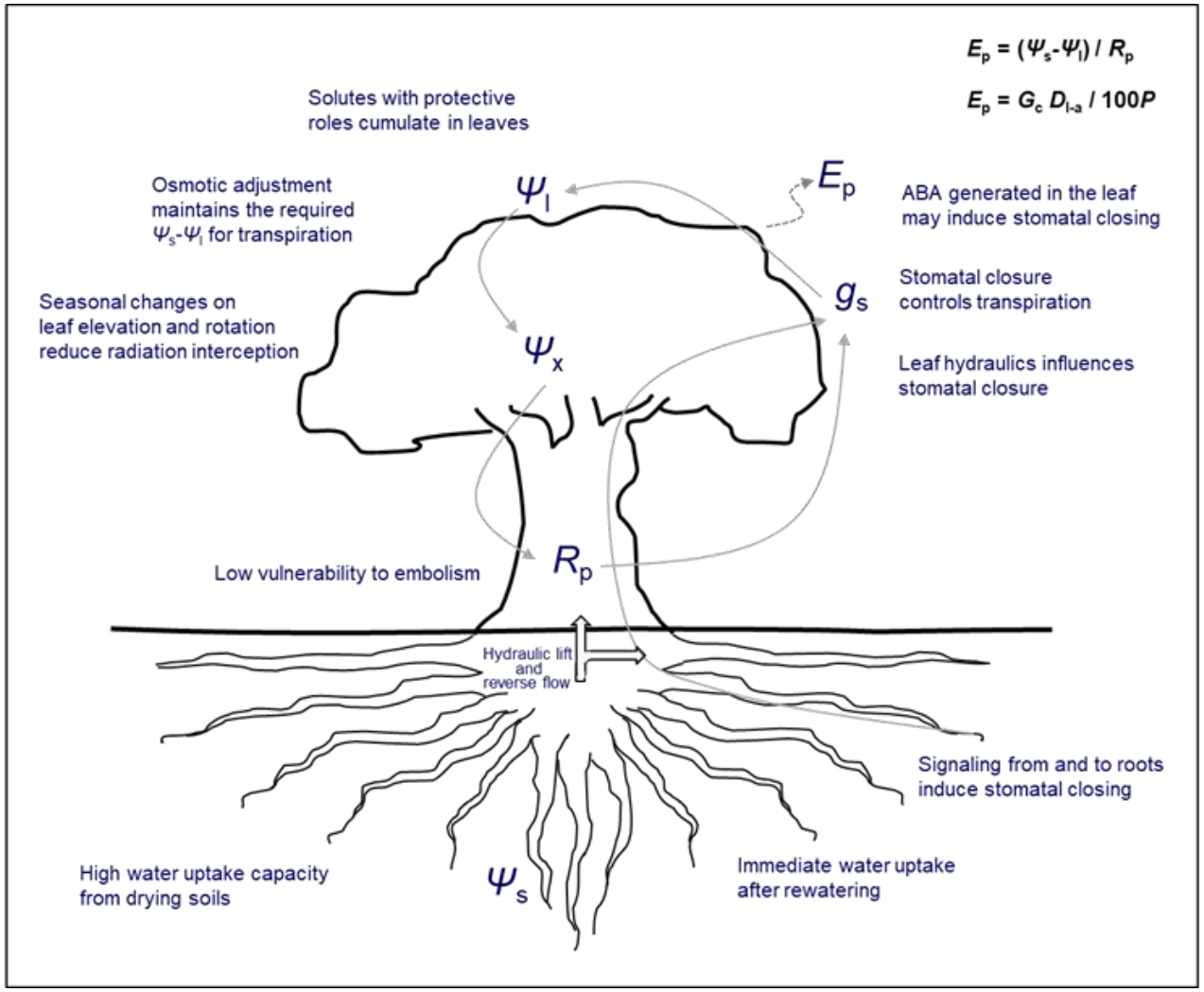
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Deficit irrigation strategies

Irrigation strategy	Definition	Example
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Sustained deficit irrigation[1] (SDI)	A fraction of IN is applied throughout the season	Vita-Serman et al (2021)
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Full localised irrigation (FI)[1]	Irrigation to replace the crop water needs	Fernández et al. (2020)

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Mechanisms related to plant transpiration



J.-E. Fernández / Environmental and Experimental Botany 103 (2014) 158–179

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Signaling & transpiration



35 year-old 'Manzanilla' olive trees planted at 7 m × 5 m
Root zone volume ≈ 25 m^3



T3. Dry-farming

Volume of the root zone wetted by irrigation ≈ 7-10 m^3 (20-30 %).

M.V. Cuevas et al. *(2010)*

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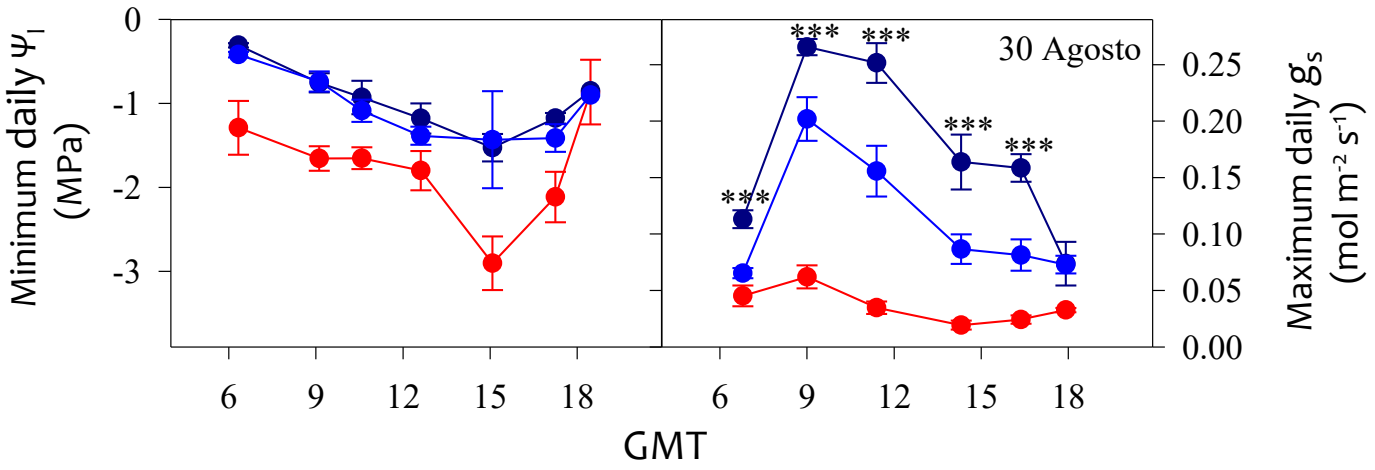
Signaling & transpiration

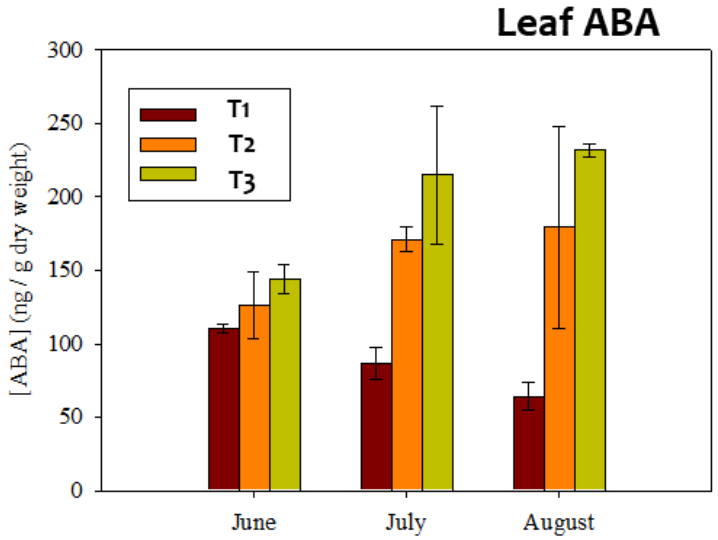




T3. Dry-farming

M.V. Cuevas et al. *(2010)*





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Signaling & transpiration





T3. Dry-farming

E_p increased ca. 35 % when the whole root zone was wetted:

- Less hydraulic resistance in the soil and soil-root interface.
- Lower stomatal control of transpiration because the root-to-shoot signaling mechanism disappeared.

This means a FI treatment applied with a localised irrigation system is a deficit irrigation treatment.

M.V. Cuevas et al. / Agricultural Water Management 97 (2010) 1293–1302

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The ‘recommended’ irrigation

FULL IRRIGATION:

$$IN = ET_c - P_e$$

RECOMMENDED IRRIGATION:

$$IN = ET_c - P_e - AD$$ Irrigation in areas where water is scarce

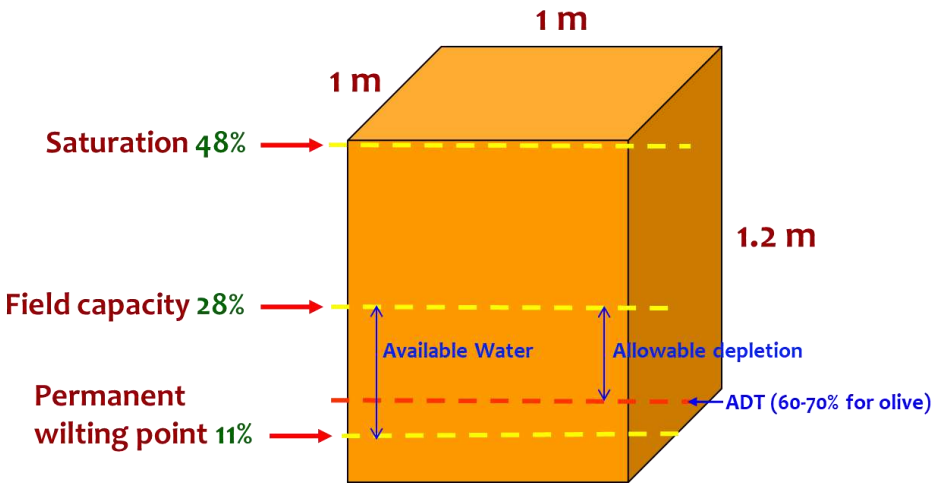


Table 3. Management allowable depletions (MAD) and maximum root zone depths for selected crops.

Type of crop	*MAD**	*Maximum root depth (ft.)***
Cotton	0.65	3.3 – 5.6
Barley and oats	0.55	3.3 – 4.5
Maize	0.50 – 0.55	2.6 – 6.0
Sorghum	0.50 – 0.55	3.3 – 6.6
Rice	0.20	1.6 – 3.3
Beans	0.45	1.6 – 4.3
Soybeans	0.50	2.0 – 4.1
Alfalfa	0.50 – 0.60	3.3 – 9.9
Cool season – Turf grass	0.40	1.6 – 2.2
Warm season – Turf grass	0.50	1.6 – 2.2
Citrus	0.50	2.6 – 5.0
Walnut orchard	0.50	5.6 – 8.0
Carrots	0.35	1.5 – 3.3
Cantaloupes/watermelons	0.40 – 0.45	2.6 – 5.0
Lettuce	0.30	1.0 – 1.6
Onions	0.30	2.0 – 3.0
Potatoes	0.65	1.0 – 2.0
Sweet peppers	0.30	1.6 – 3.2
Cucumbers	0.50	2.0 – 4.0

* MAD values are for crop water use of 0.20 inch/day
** Root depths can vary with soil and other conditions. Effective root depth is usually shallower.
Source: Allen et al. (1998)

SOURCE: Oklahoma Cooperative Extension Service BAR.1537, by S. Datta, S. Taghvaeian ans J. Stivers, June 2017

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The ‘recommended’ irrigation

Crop	Full irrigation (m^3/ha)	Recommended irrigation* (m^3/ha)
Conventional olive	1600 - 2000	1300 - 1700
Intensive olive	2600 – 3200	2200 - 2800
Superintensive olive	3500 – 4200	2800 - 3400
Almond	7400 – 7800	5000 - 7000
Walnut	7400 – 7800	6000 – 7000
Pistachio	4800 – 6800	4600 – 6000
Citrus	4500 - 5000	4000 – 4500
Stone fruits	6800 - 7300	4500 - 5500

* Values for soils with a medium to high water retention capacity.
It may imply some yield reduction (~ 10%)

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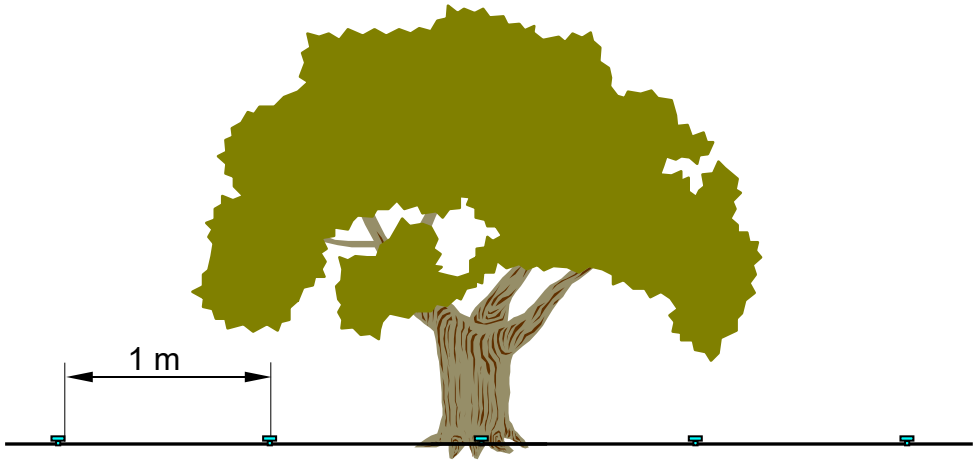
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Deficit irrigation strategies

Partial rootzone drying (PRD)

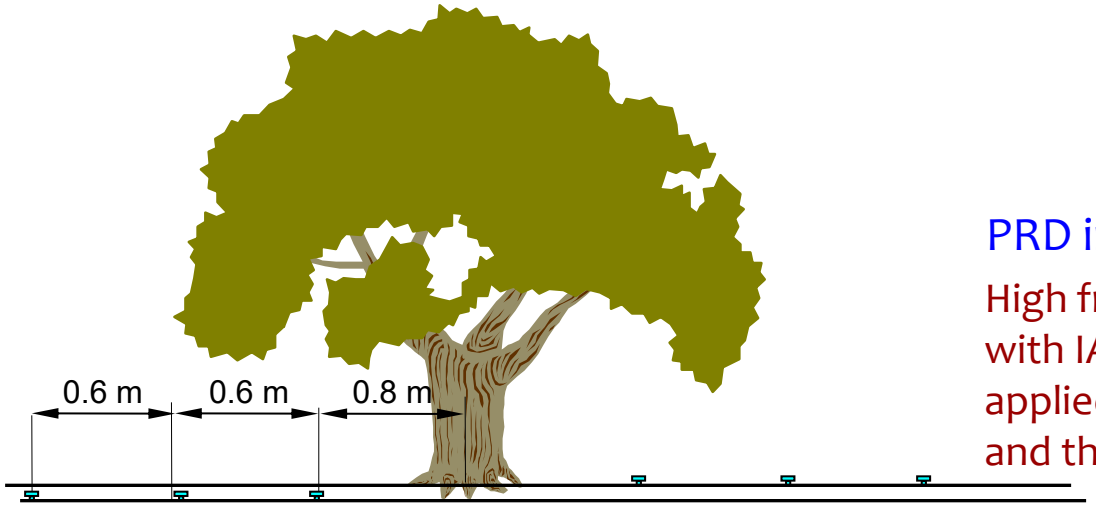
$IA_{RDI} \approx IA_{PRD}$, but the water supply is switched from one side of the tree to the other every 2-3 weeks.

IA = irrigation amount



Sustained Deficit irrigation

High frequency irrigation
with IA = 50-70 % IN
applied to both sides of he tree



PRD irrigation

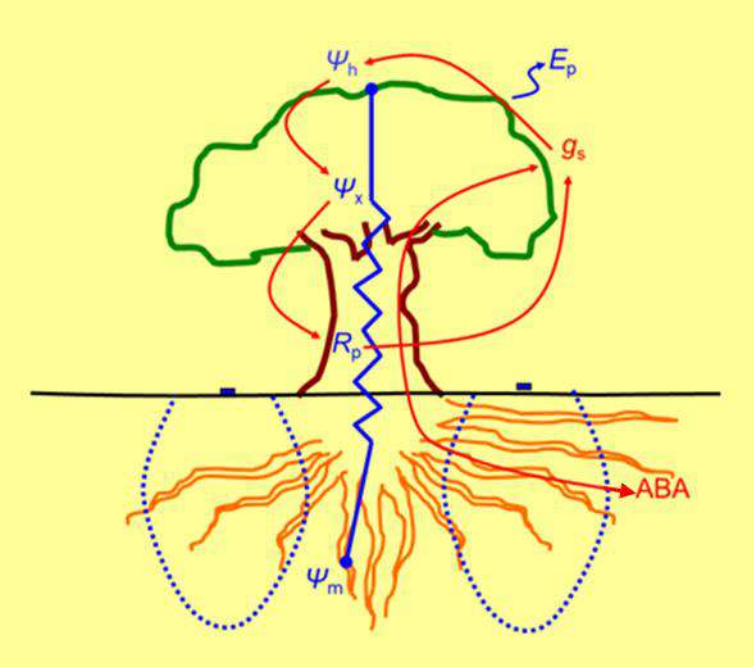
High frequency irrigation
with IA = 50-70 % IN
applied to one side for 2-3 weeks
and then shifted to the other side

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Deficit irrigation strategies

Partial rootzone drying (PRD)

$IA_{RDI} \approx IA_{PRD}$, but the water supply is switched from one side of the tree to the other every 2-3 weeks.



Plant Soil (2006) 284:273–291
DOI 10.1007/s11104-006-0045-9

RESEARCH ARTICLE

Water relations and gas exchange in olive trees under regulated deficit irrigation and partial rootzone drying

J. E. Fernández · A. Díaz-Espejo · J. M. Infante · P. Durán · M. J. Palomo · V. Chamorro · I. F. Girón · L. Villagarcía

FI 100%
RDI 50%
PRD 50%

PRD is not effective when loalised irrigation wets just a fraction of the root zone.

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Deficit irrigation strategies

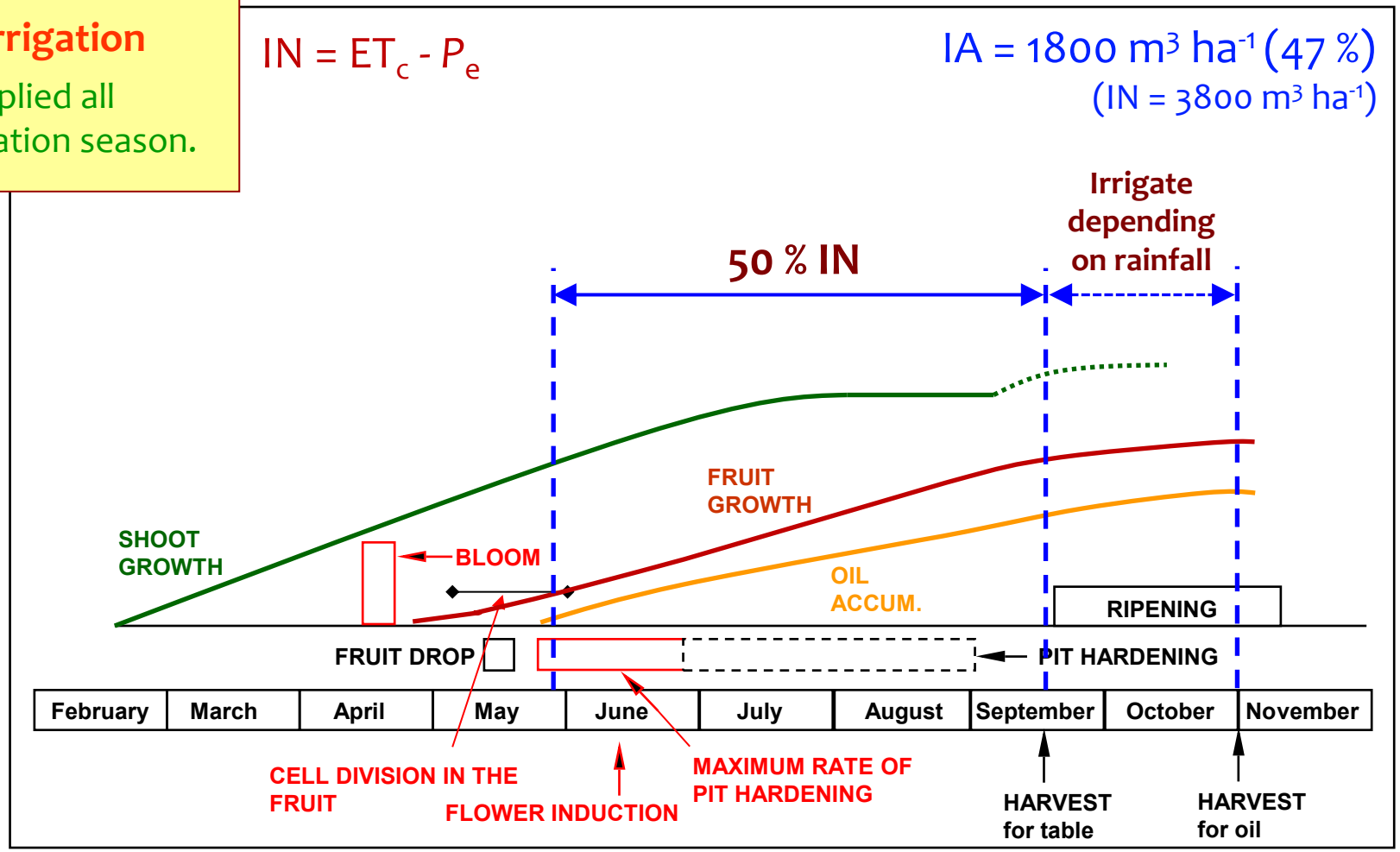
Irrigation strategy	Definition	Example
Supplementary or complementary irrigation	A single irrigation event when water stress is severe. Just 2 or 3 irrigation events per season	Lavee at al. (1990)
Low frequency irrigation	The soil is left to dry until the readily available water is consumed. Then the soil is irrigated to field capacity and left to dry again.	Lavee and Wodner (1991)
Sustained deficit irrigation[1] (SDI)	A fraction of IN is applied throughout the season	Vita-Serman et al (2021)
Regulated deficit irrigation (RDI)[1]	Irrigation is reduced at the stages at which the crop is more tolerant to water stress. For the rest, IA = 100 % IN	Branquinho (2021)
Partial root zone drying (PRD)[1]	A fraction of IN is applied throughout the season, switching irrigation from one side of the tree to the other every 2-3 weeks (two laterals required)	Maesano et al. (2021)
Irrigation above ADT[1]	Irrigation to maintain the stored soil water above the allowable depletion threshold (ADT)[2]	Orgaz et al. (2017)
Full localised irrigation (FI)[1]	Irrigation to replace the crop water needs	Fernández et al. (2020)

Deficit irrigation strategies

Sustained deficit irrigation

A fraction of IN is applied all throughout the irrigation season.

The olive growing cycle in SW Spain



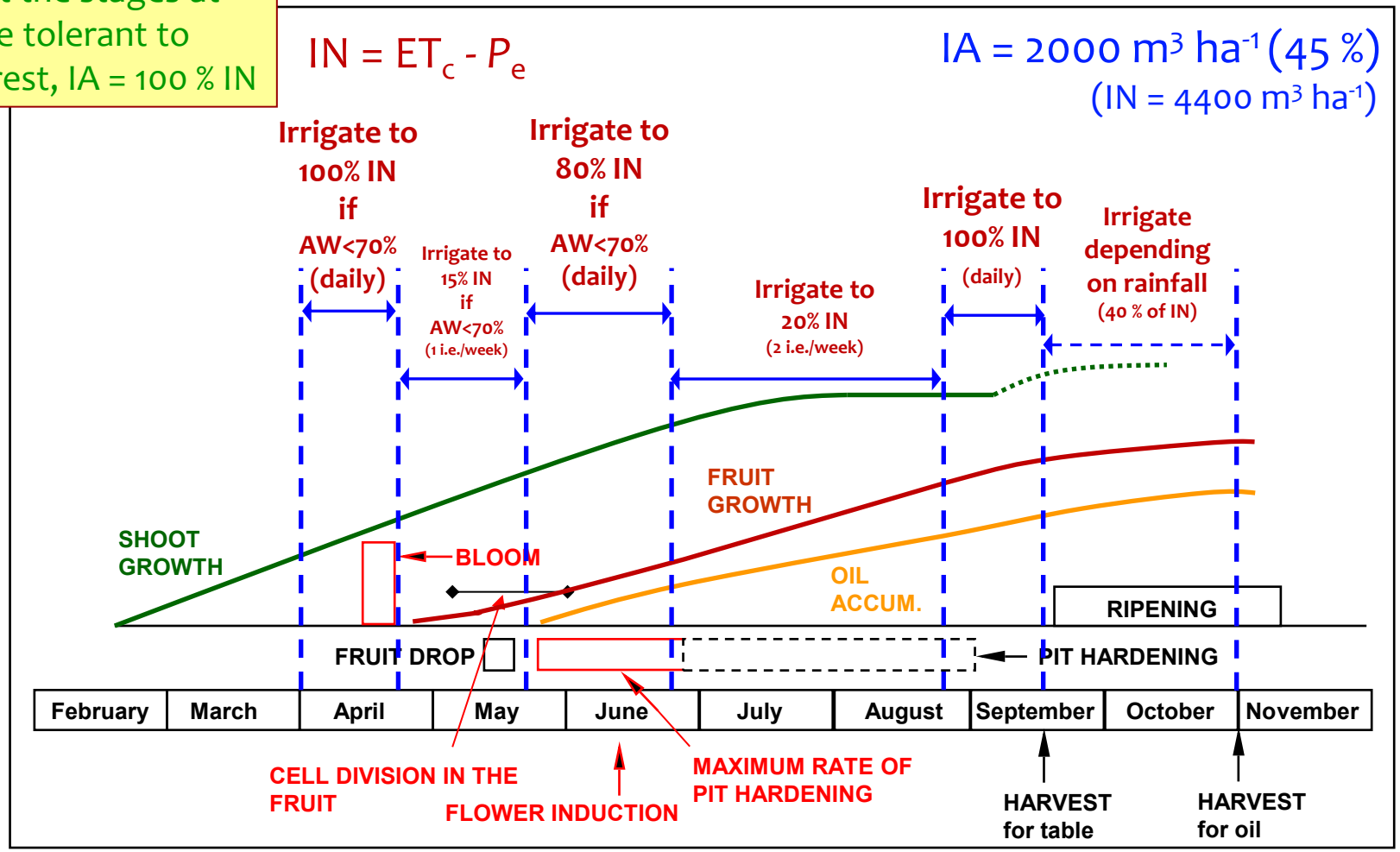
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Deficit irrigation strategies

Regulated deficit irrigation (RDI)

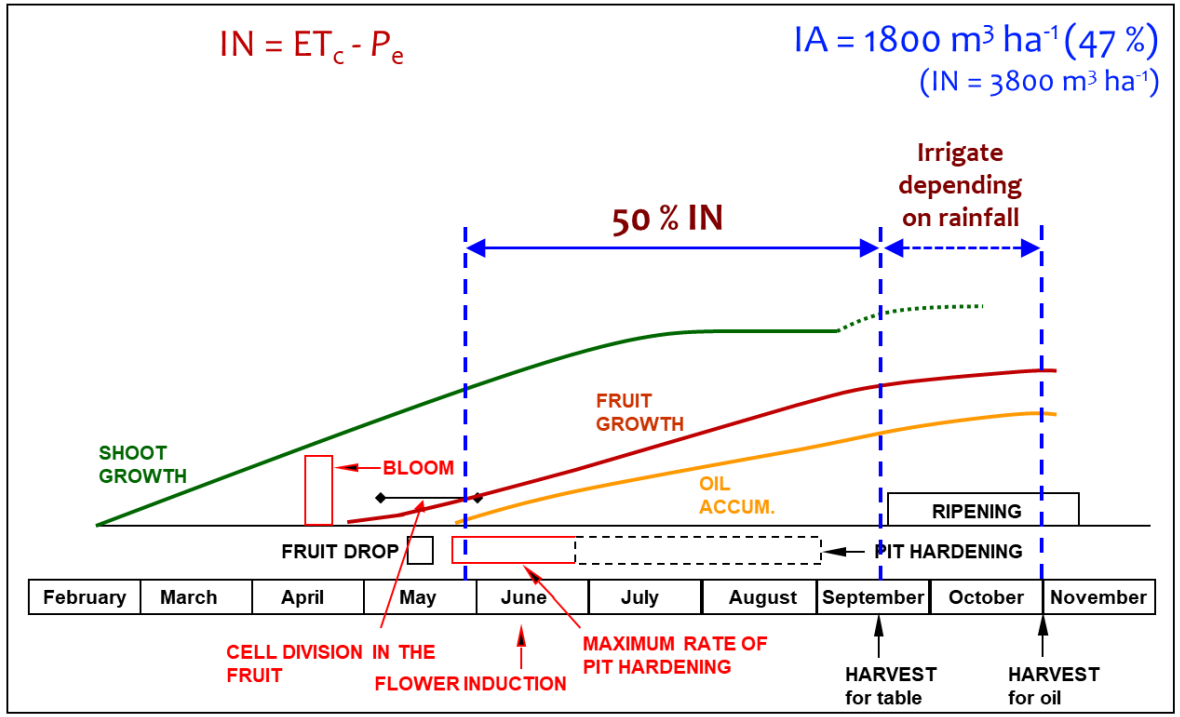
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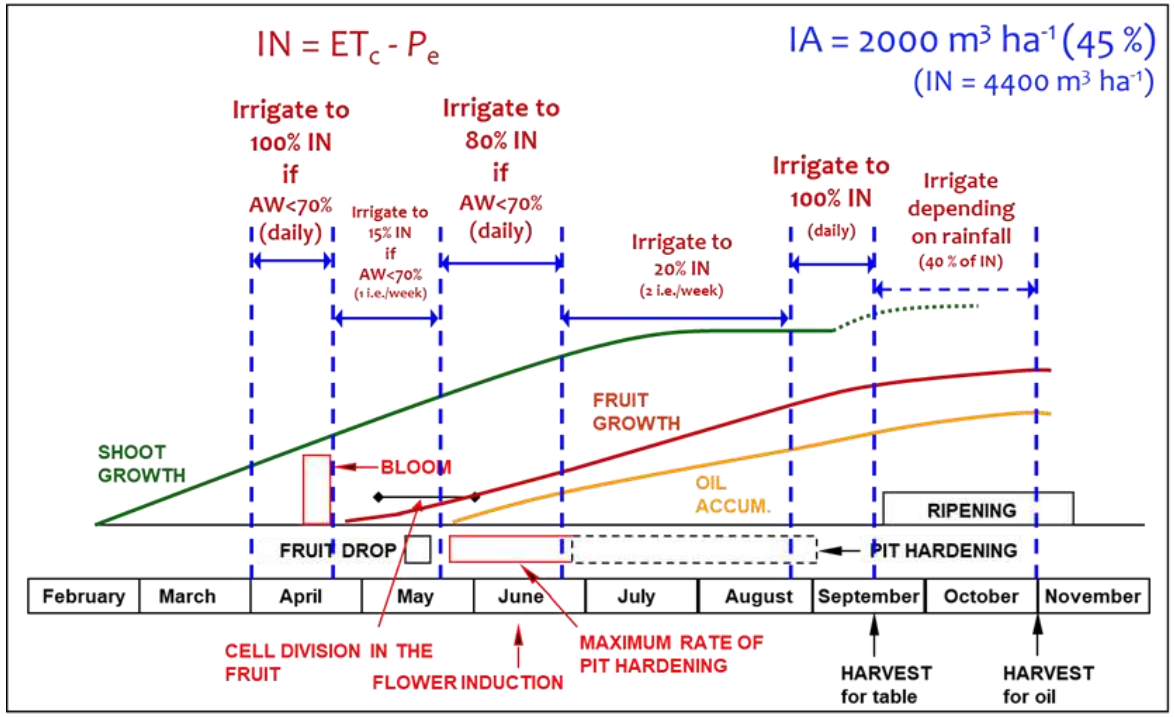
The olive growing cycle in SW Spain



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Sustained vs. Regulated Deficit Irrigation

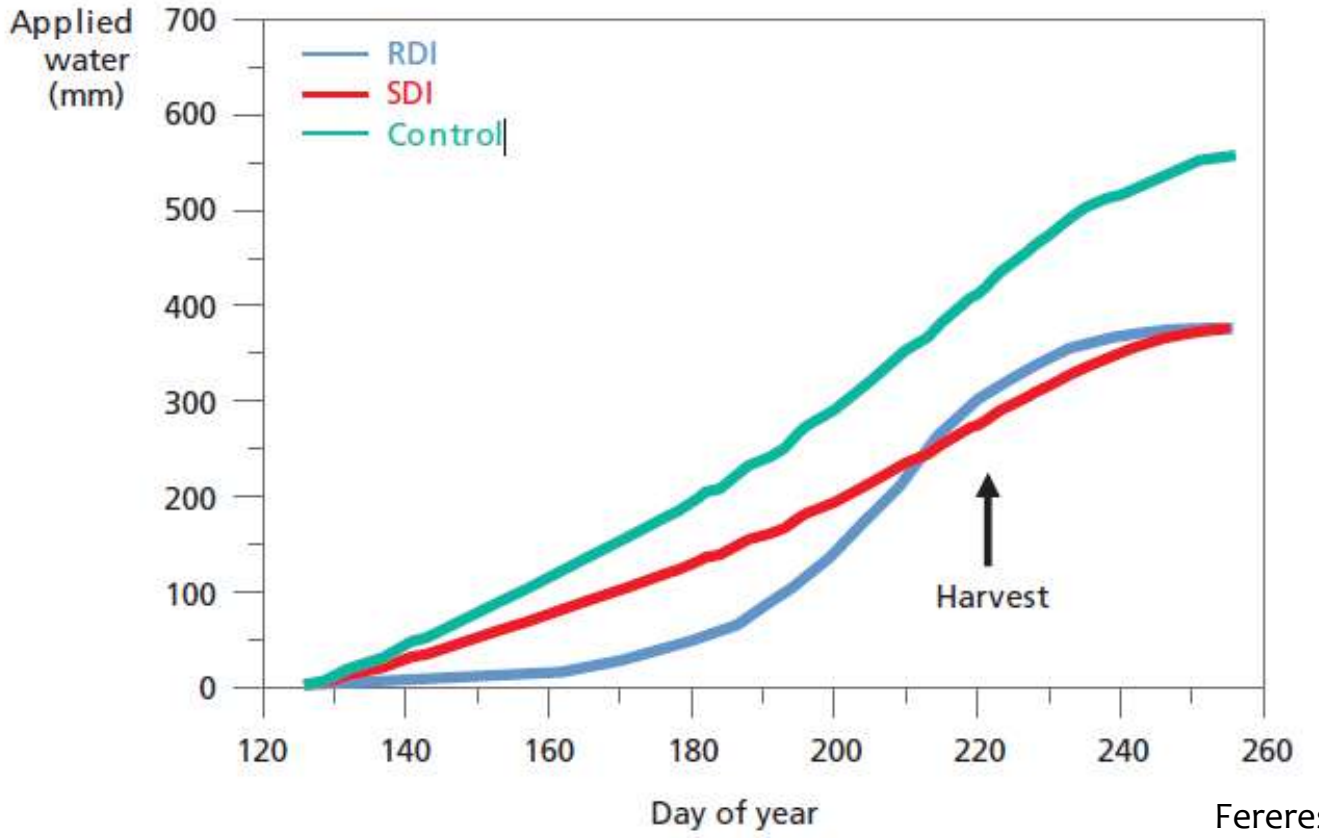




For olive, there is not a consensus on whether RDI is better tan SDI

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Sustained vs. Regulated Deficit Irrigation



Fereres et al. (2012)

Differences can be greater when fruit size is important (e.g. peach)

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The impact of severe deficit irrigation

OLIVE

Irrigation %	Fruit yield %
100	100
60	77
45	75
30	59
22	47
12	22

→ LA = 57% Oil yield = 75%

Better oil quality

Watch out! Quality can be ruined if rain falls before harvesting

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The impact of severe deficit irrigation

ALMOND

Irrigation %	Fruit yield %
100	100
70	88
35	60

CITRUS

Irrigation %	Fruit yield %
100	100
80	90
70	90 – 80
60	70*

* reduced fruit size

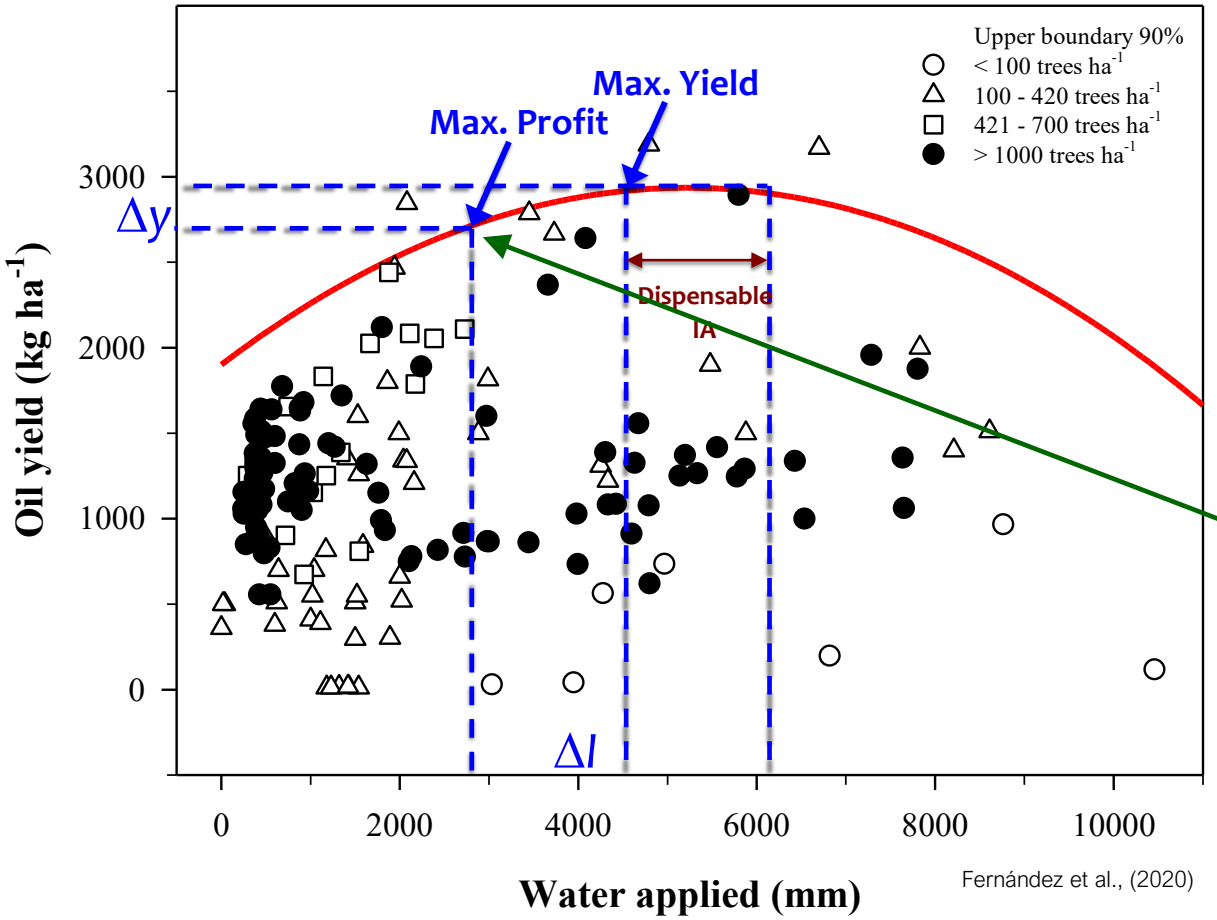
STONE FRUITS: greater impact on fruit size if DI occurs in Phase I (cell division) or Phase III (cell growth)

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Deficit irrigation (DI) for maximum profit (MP)

Production target = maximum yield

Production target = maximum profit



Fernández et al., (2020)

The crucial question is:

Where, in the curve, is this point?

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DI for MP = the economic analysis approach

Agricultural Water Management 237 (2020) 106074

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

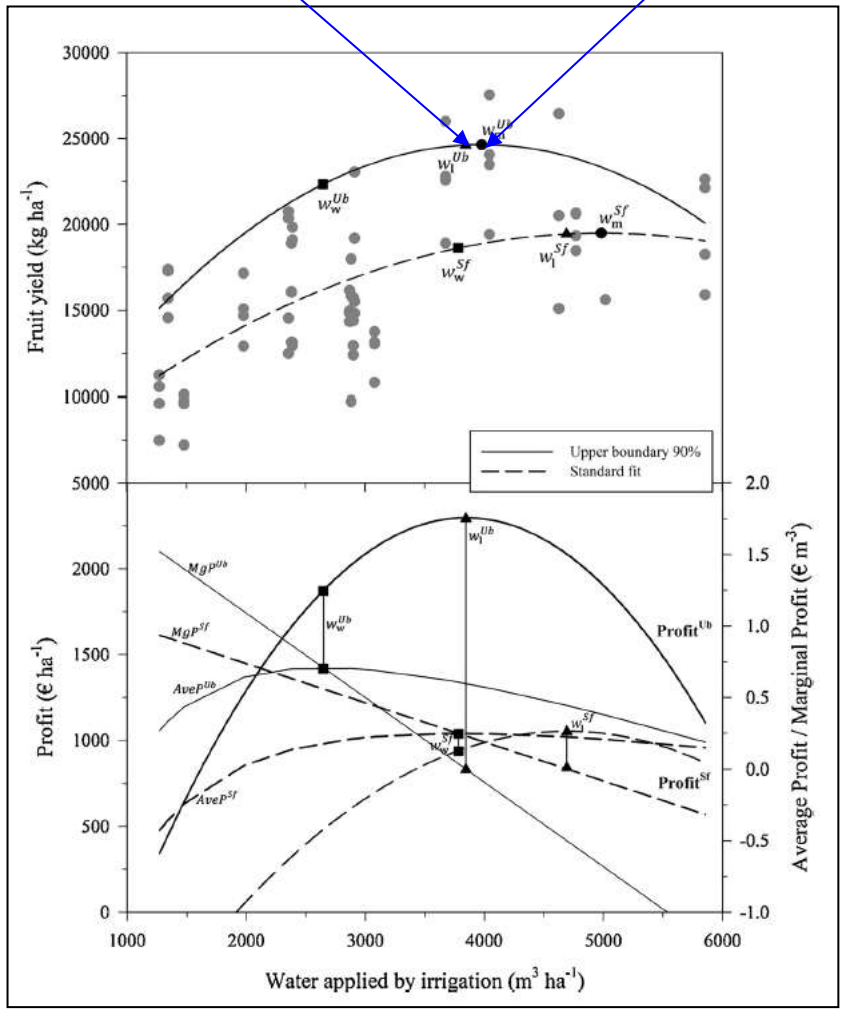
Water use indicators and economic analysis for on-farm irrigation decision: A case study of a super high density olive tree orchard

J.E. Fernández[a,*], F. Alcon[b], A. Diaz-Espejo[a], V. Hernandez-Santana[a], M.V. Cuevas[a]

[a] Irrigation and Crop Ecophysisology Group, Instituto de Recursos Naturales y Agrobiología de Sevilla, Avenida Reina Mercedes, 10, 41012, Sevilla, Spain
[b] Departamento de Economía de la Empresa, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain

3845 m³/ha (max. profit)

3981 m³/ha (max. yield)



The point of MP will be far away from that of MY if:

- The grower is paid by quality
- Electricity is expensive
- Water is expensive

If not, MP is achieved for irrigation amounts close to those required for MY.

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DI for MP = the economic analysis approach

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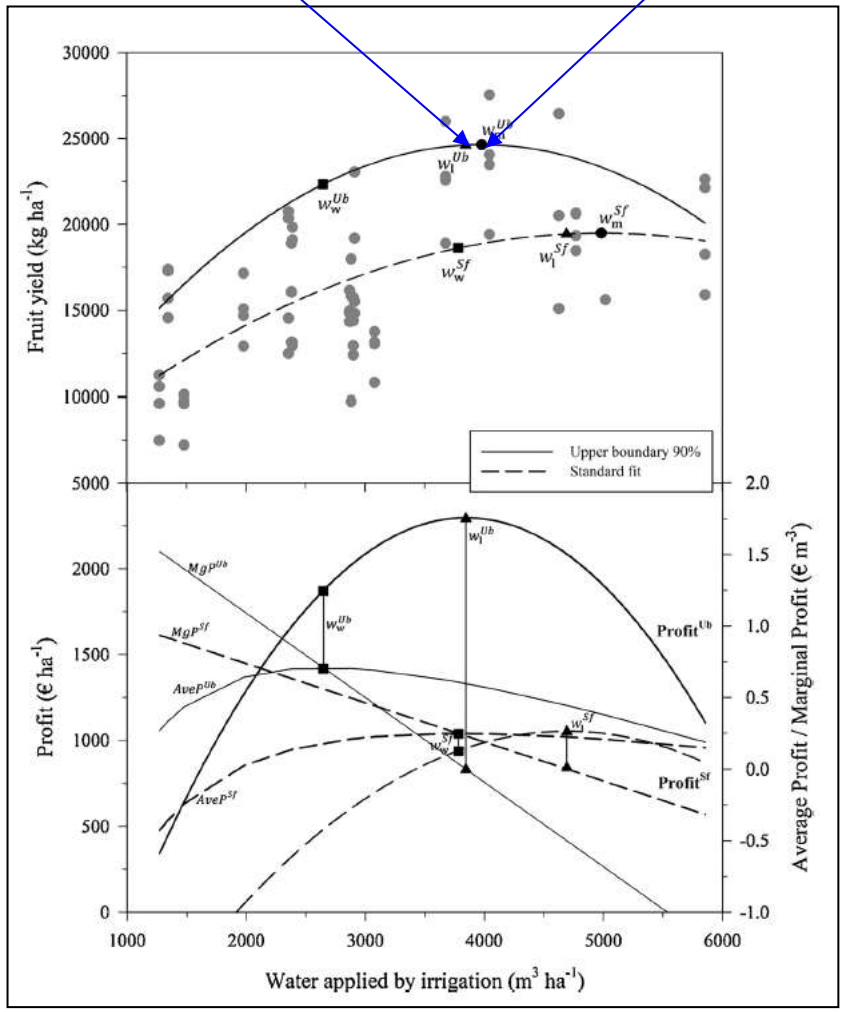
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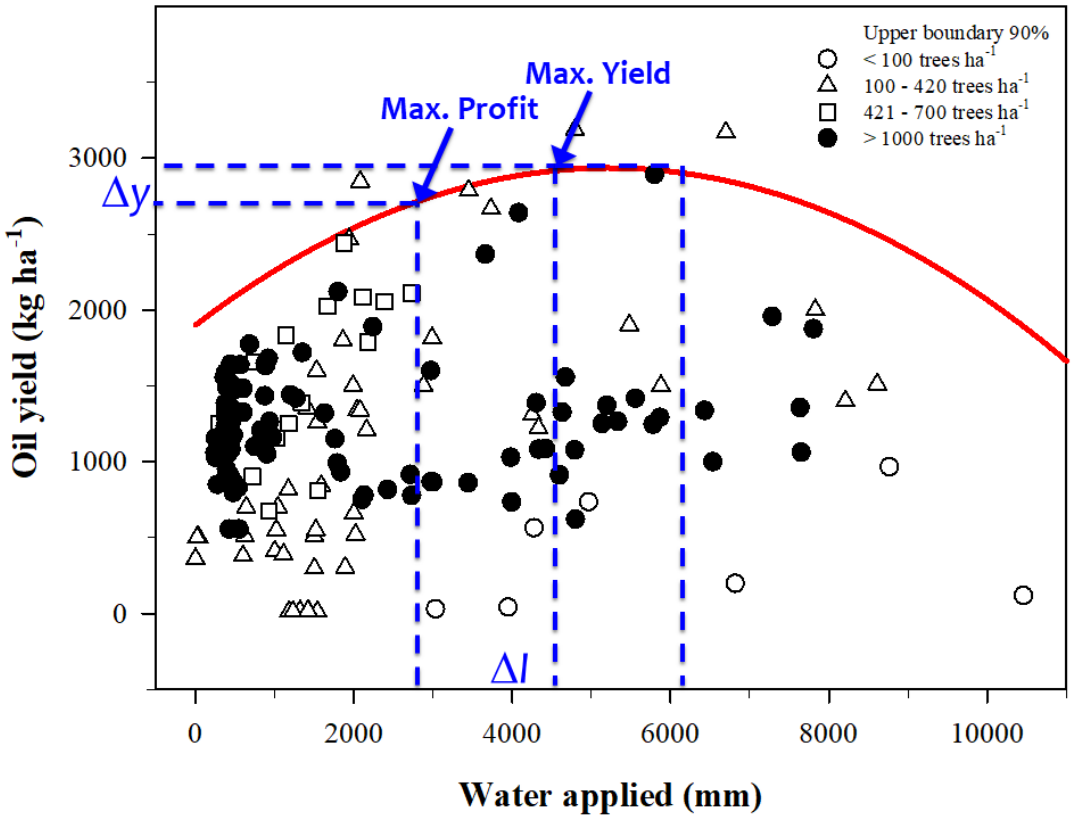
¿What to do if the available water is low?

1. To apply FI to a reduced fraction of the orchard
2. To apply DI to a greater fraction of the orchard

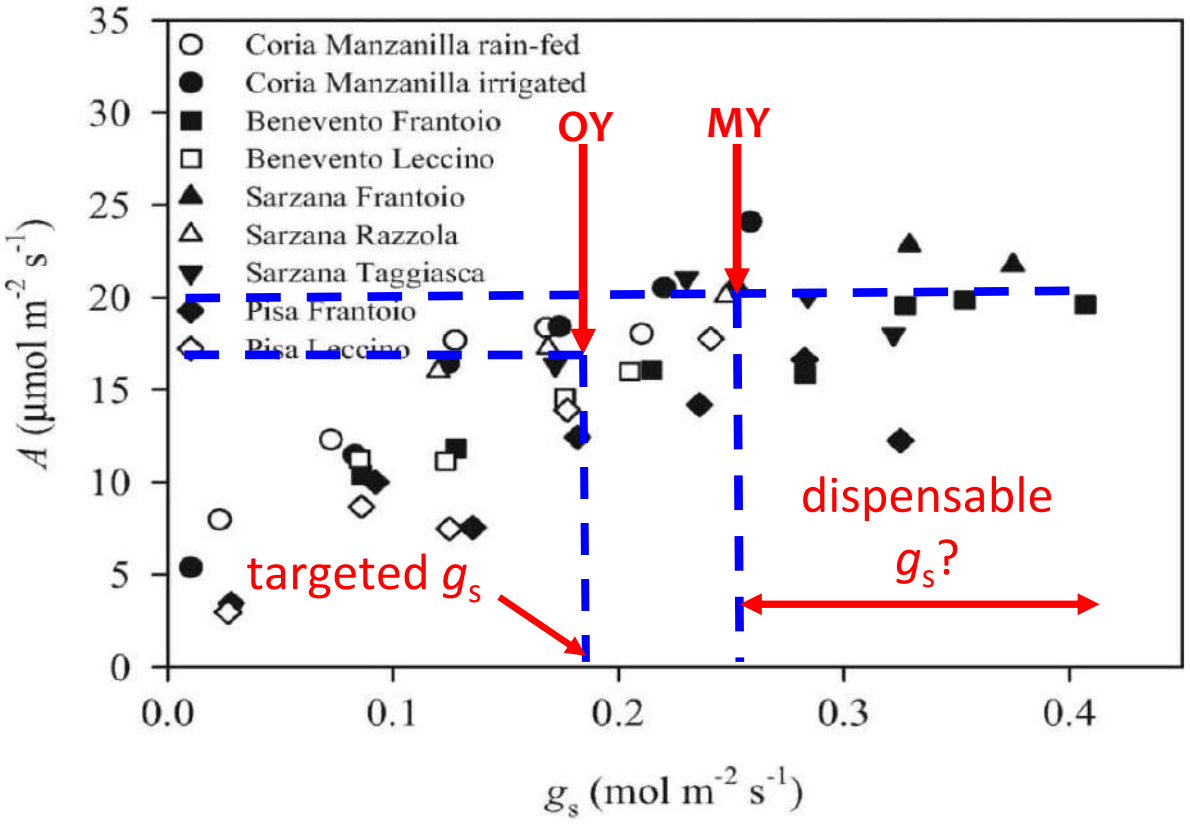
For a 10 ha olive orchard with 1500 m³/ha

1. To irrigate 3,9 ha with 3845 m³/ha
2. To irrigate 5,7 ha with 2648 m³/ha

DI for MP = the stomatal conductance approach



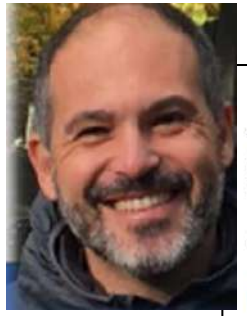
Fernández et al., (2020)



Fernández et al., (2008)

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DI for MP = the stomatal conductance approach



Agricultural Water Management 114 (2012) 37–49

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Steps toward an improvement in process-based models of water use by fruit trees: A case study in olive

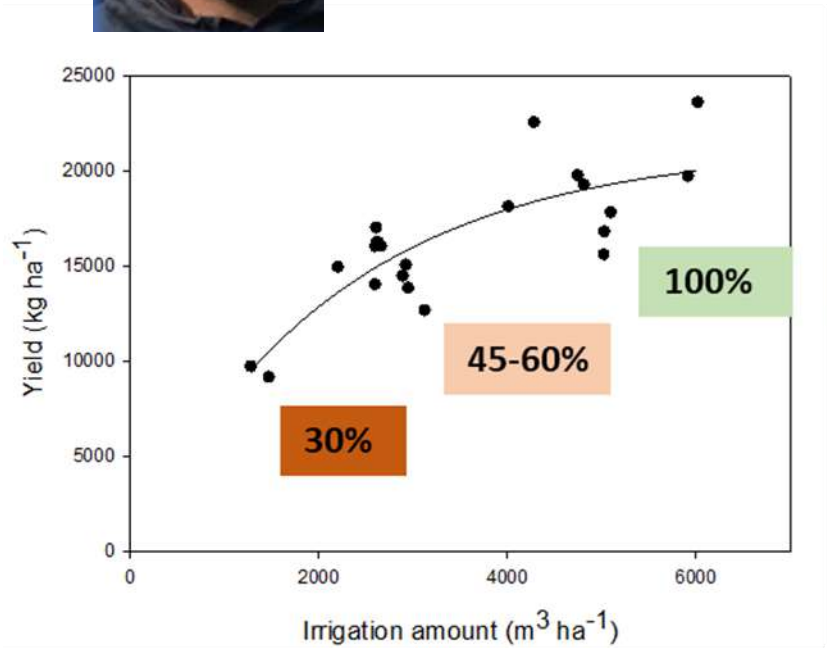
A. Diaz-Espejo[a,e,*], T.N. Buckley[b,e], J.S. Sperry[c,e], M.V. Cuevas[a,e], A. de Cires[d,e], S. Elsayed-Farag[a,e], M.J. Martin-Palomo[f,e], J.L. Muriel[f,e], A. Perez-Martin[a,e], C.M. Rodriguez-Dominguez[a,d,e], A.E. Rubio-Casal[d,e], J.M. Torres-Ruiz[a,e], J.E. Fernández[a,e]

$$g_s = \frac{\chi\beta\tau\left(\Psi_s + \pi_e\right)}{1 + \chi\beta\tau R\,VPD}$$

A simplified version of the hydromechanical model by Buckley, Mott and Farquhar (2003)

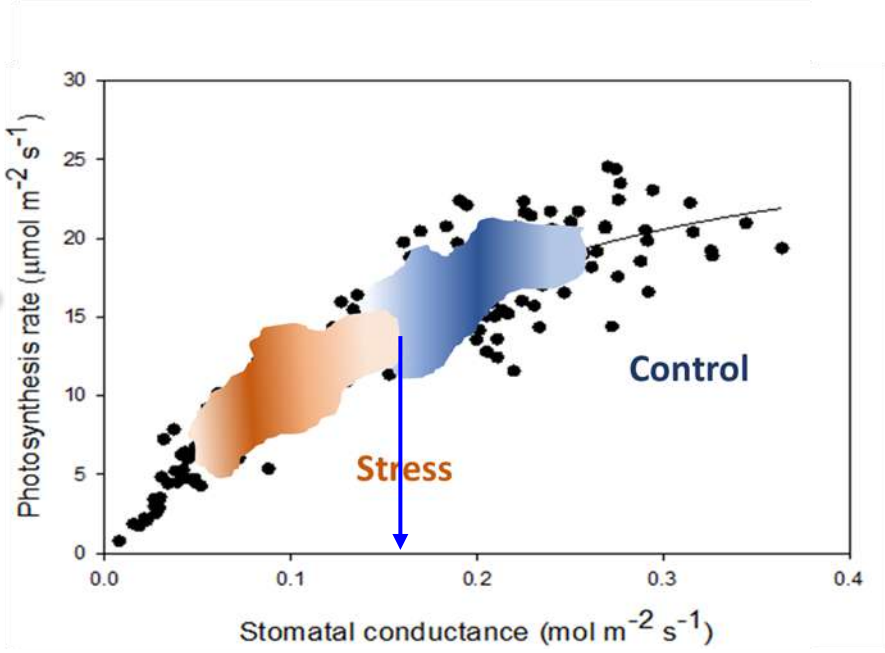
DI for MP = the stomatal conductance approach





Conceptual basis

Analogous



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DI for MP = the stomatal conductance approach



Agricultural and Forest Meteorology 218–219 (2016) 92–101

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit

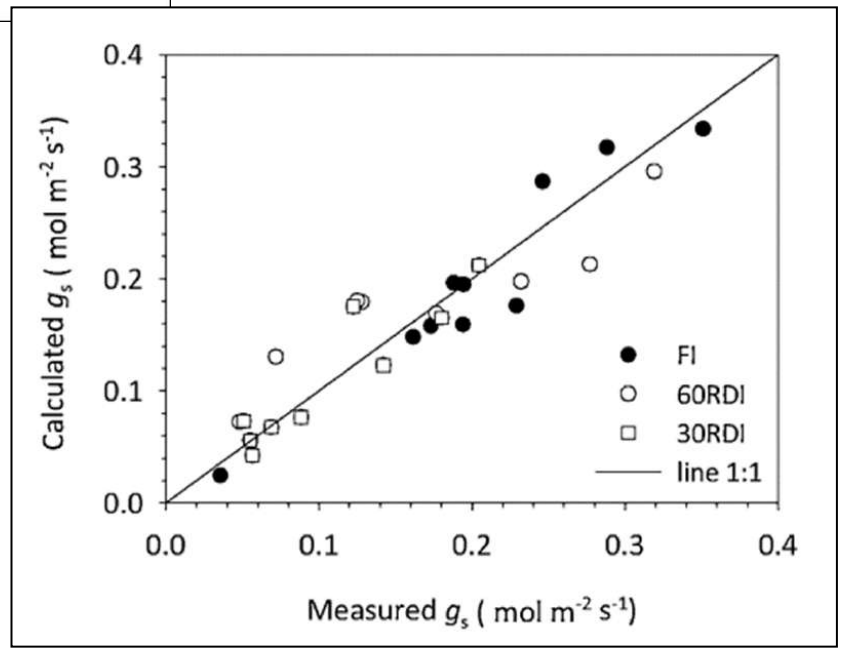
V. Hernandez-Santana [a], J.E. Fernández [a], C.M. Rodriguez-Dominguez [a,b], R. Romero [a], A. Diaz-Espejo [a,*]







$g_s \approx J_s / D_a$

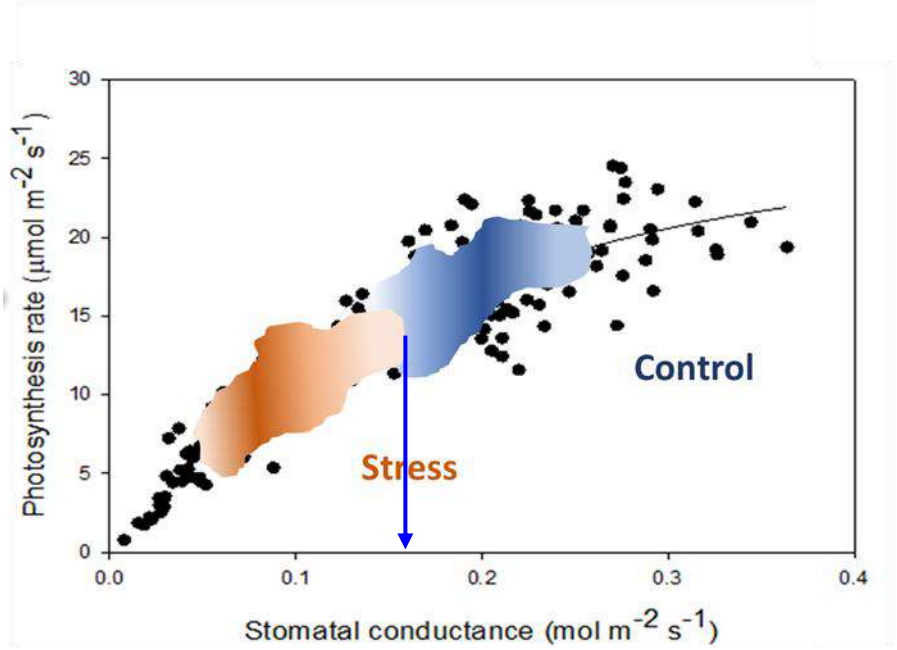


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DI for MP = the stomatal conductance approach



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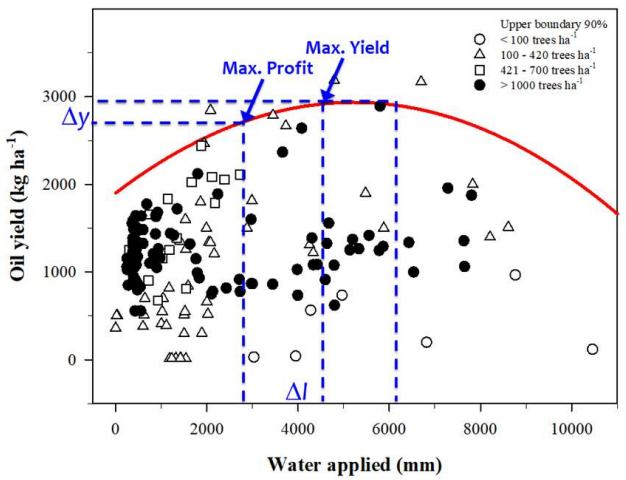


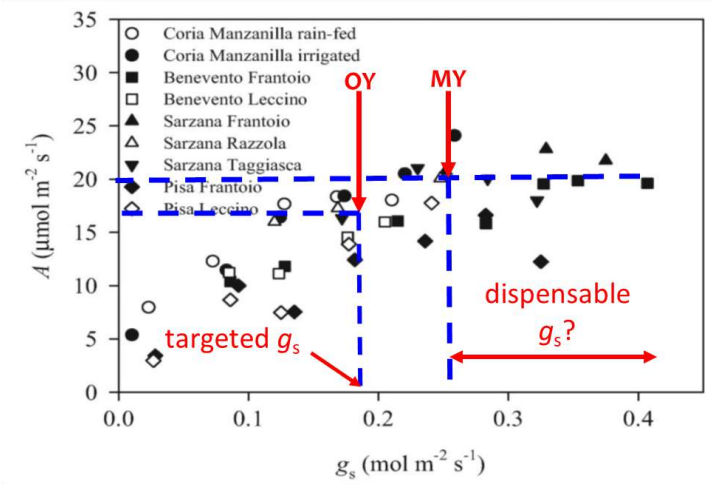
IAs are adjusted for the estimated g_s in the orchard to be as close as possible to the targeted g_s

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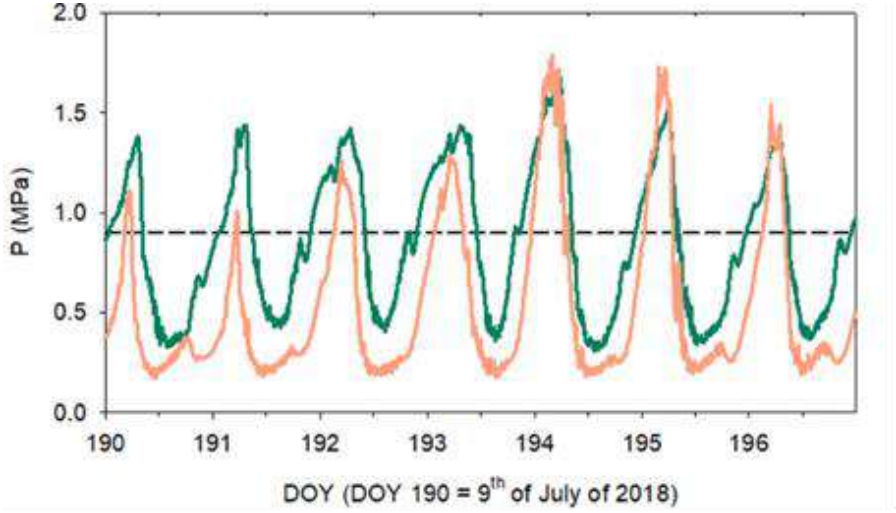
Should we rely on stomatal conductance only?

The A_N-g_s relationship has been used as a proxy of yield-water used…





…but nowadays we study other variables more useful to schedule irrigation



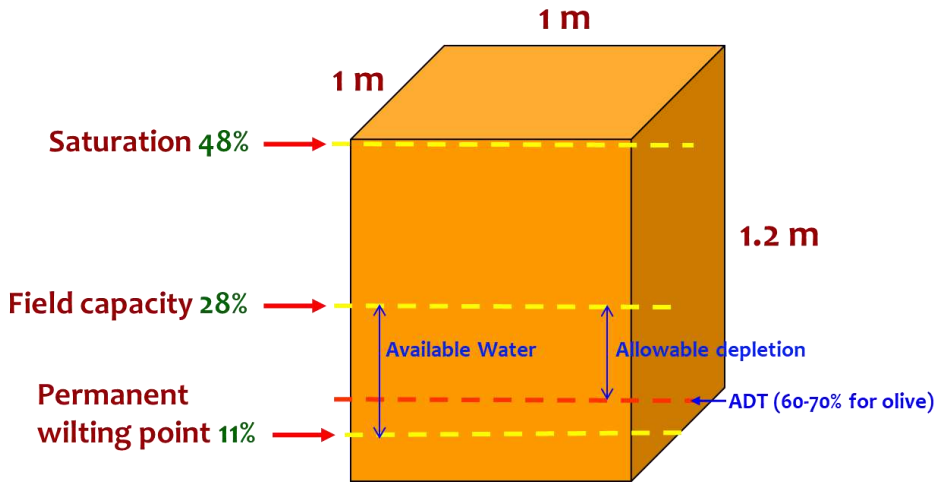




Coussement et al., (2021)
Hernandez-Santana et al., (2021)

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DI for MP = the soil matric potential approach



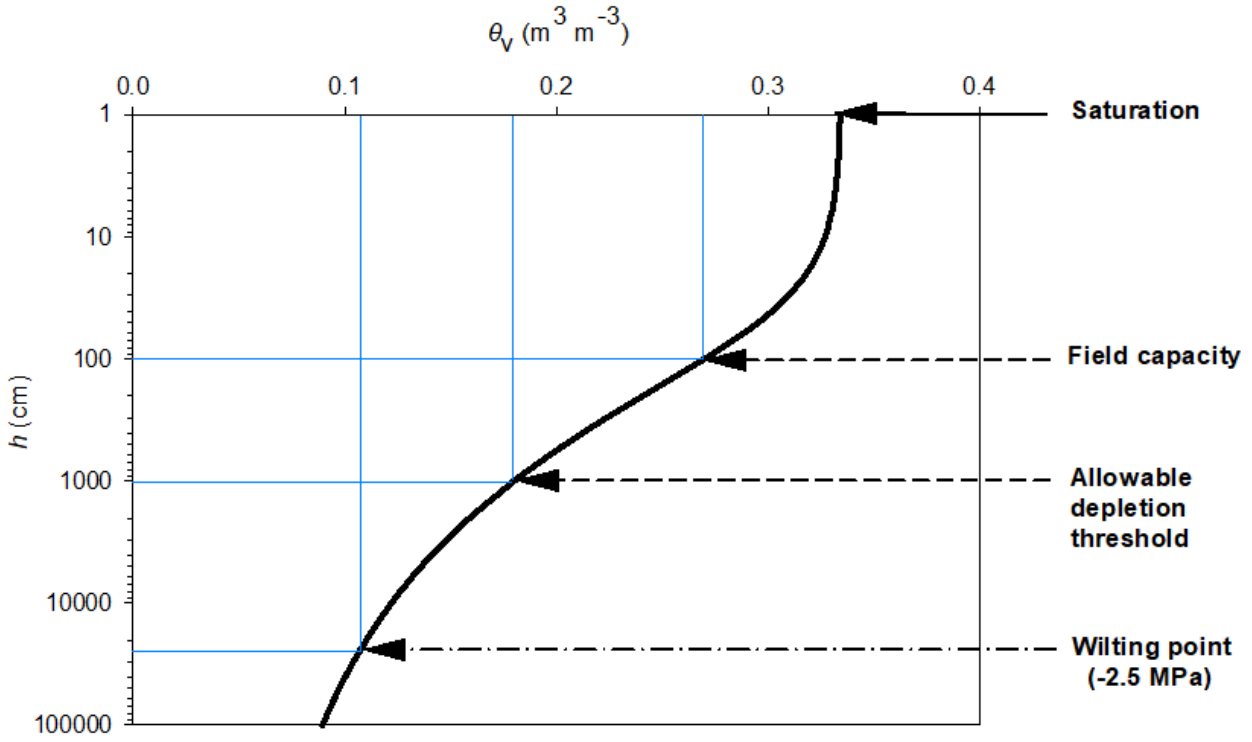


Figure SP1. Water retention curve calculated with the Rosetta pedotransfer function and textural values measured in the orchard. For olive, the wilting point is considered at a soil matric potential of -2.5 MPa. θ_v = volumetric soil water content; h = suction.

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DI for MP = the soil matric potential approach



The model tells me the g_s value corresponding to h = 1000 cm of water, i.e. Ψ_m = 0,1 MPa.

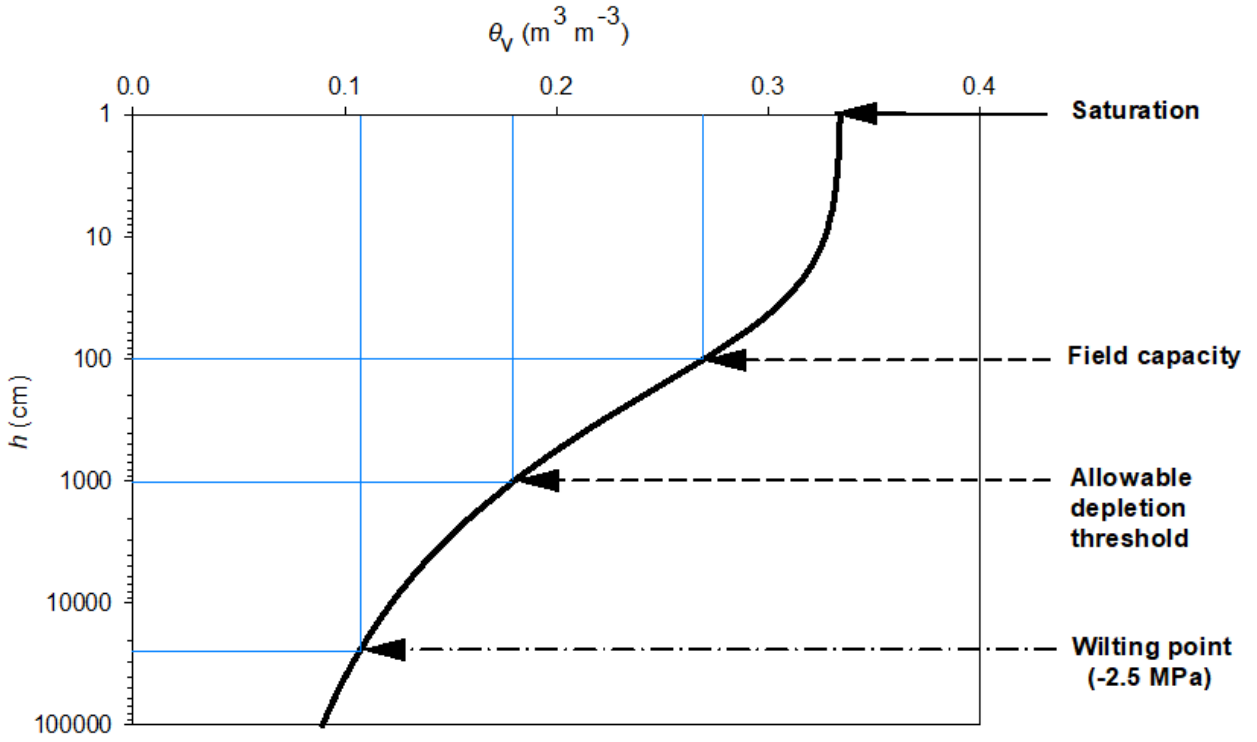
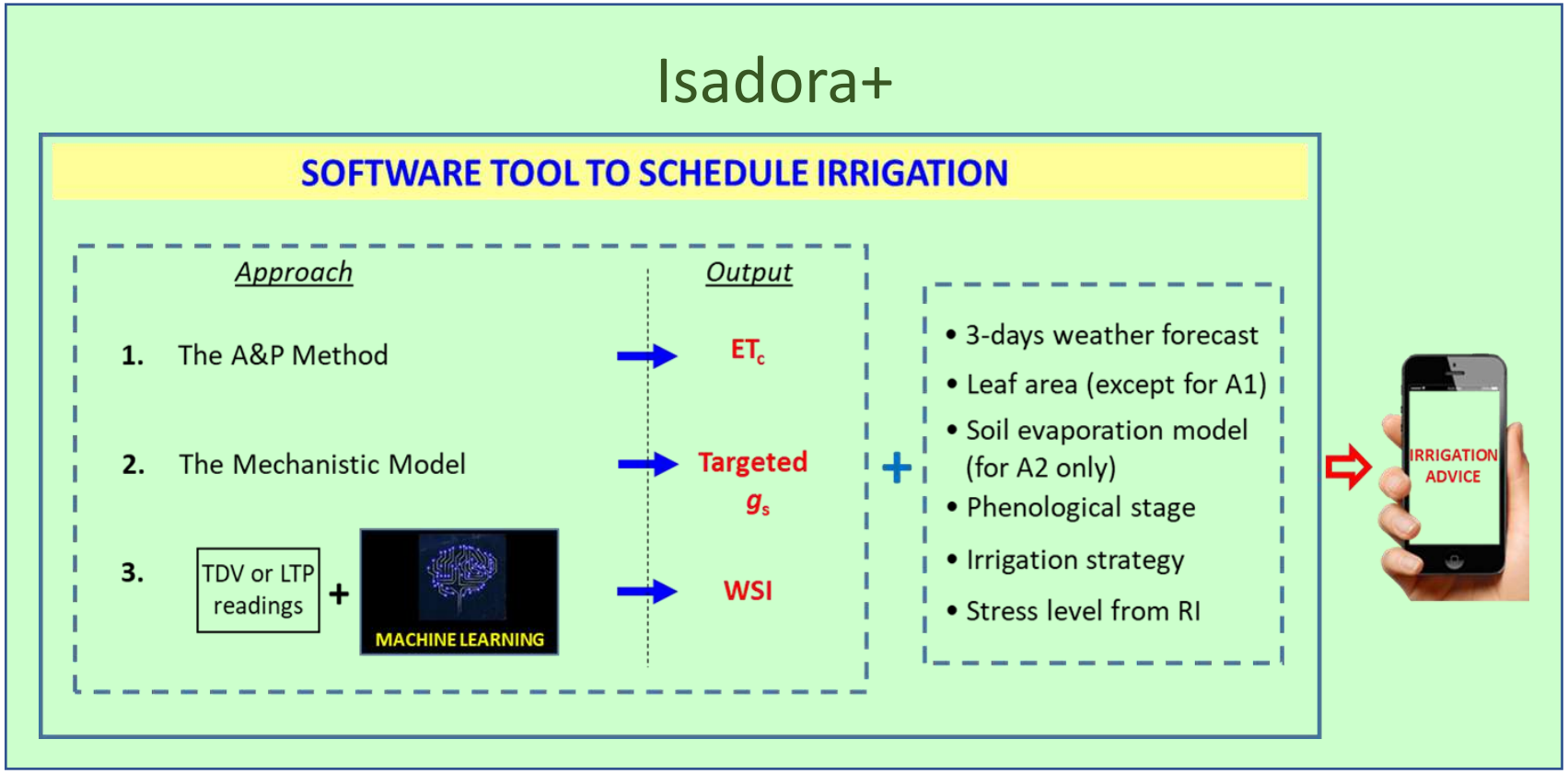


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Decision Support Systems

DDSs enable the use of these complex approaches for irrigation scheduling in commercial orchards



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Deficit irrigation under multi-year droughts



Year	Irrigation allocation* (m^3/ha)
2016	6000
2017	5500
2018	5000
2019	5400
2020	4500
2021	2800
2022	1750
2023	700

* Delivered to the growers by the Guadalquivir River Basin Confederation

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Deficit irrigation under multi-year droughts

What to do?

Before planting:
- Choose a vigorous rootstock — large root system
- Choose a suitable variety — tolerant to drought and wit low vigor
- Increase the soil water retention capacity?
- Choose the right plant density — OLIVE: 6 m x 1,75 m (952 trees/ha)

After planting:
- Increase pruning intensity — reduce leaf area for lower water demand
- Reduce number of fruits — they will demand the water that the tree may need to survive: consider not to irrigate at flowering
- Manage the orchard cover — reduce soil water evaporation

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Survival irigation

Crop	Full irrigation (m^3/ha)	Recommended irrigation (m^3/ha)	Survival irrigation (m^3/ha)	Will the trees die if you don't apply the SI dosis?
Conventional olive	1600 - 2000	1300 - 1700	250 - 500	No
Intensive olive	2600 - 3200	2200 - 2800	500 - 750	No
Superintensive olive	3500 - 4200	2800 - 3400	500 - 1000	Rarely
Almond	7400 - 7800	5000 - 7000	1000 - 1500	Yes
Walnut	7400 - 7800	6000 - 7000	1500 - 2000	?
Pistachio	4800 - 6800	4600 - 6000	500 - 1000	?
Citrus	4500 - 5000	4000 - 4500	1000 - 1500	?
Stone fruits	6800 - 7300	4500 - 5500	1000 - 1500	?

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Thanks for your attention

Thanks are also due to my research group

Questions?

The Ecophysiology and Crop Irrigation (ECOVER) group



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Plant2web. A Modular Platform for Remote Data Retrieval and Visualization



Terra vita est

Rafael Romero Vicente

rafaelromerovicente@gmail.com

@rr4v

IRNAS

Instituto de Recursos Naturales y Agrobiología de Sevilla

My institution:



Spanish National Research Council

- **120 research centers**
- 11k workers
- 3.7k researchers

My research center:



Institute of Natural Resources and Agrobiology of Seville

Purpose:

"Use and conservation of soil-plant-water natural resources"

My research group:



Irrigation and Crop Ecophysiology Group

Objective:

"Optimize the use of water in agriculture"

8 doctors+1 graduate+1 technician

A Need for automation

Collecting data from experiments



Dendrometers



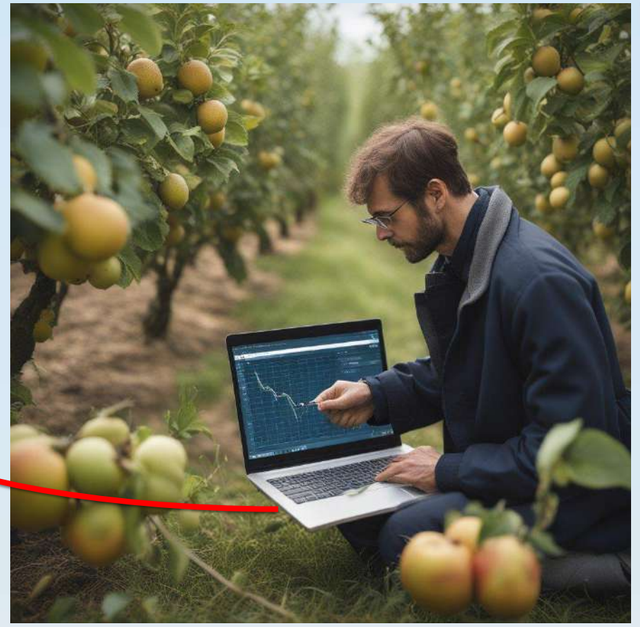
Sap flow sensors



Leaf turgor sensors

Wires





Problems of manually collecting:

- Time consuming process
- Significant allocation of human resources
- Potential for human error / security and data integrity
- Data delay / limited real-time monitoring
- Scaling challenges

Our Solution: Plant2web

A Modular Platform for Remote Data Retrieval and Visualization



Sensors

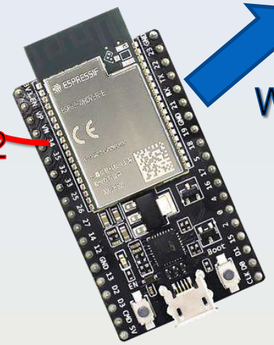
Wires





Dataloggers

RS-232



ESP32

WiFi

WiFi



Outdoor Router 4G / WiFi

4G



CSIC Server

WiFi / Ethernet



WEBS

Main menus





Main menus for
projects and experimental stations

Sensor/graph selection

Digiorchard (La Hampa)

Almendro Linea L (Lejos del cortijo)

Flujo de savia (Tzs)
Dendrometros de tronco
Dendrometros de fruto
Agua en suelo (Graficas)
Zims (graficas)

Almendro Linea C (Cerca del cortijo)

Flujo de savia (Tzs)
Dendrometros de tronco
Dendrometros de fruto
Agua en suelo (Graficas)
Zims (graficas)

Limonero P7 (Lejos del camino)

Flujo de savia (Tzs)
Dendrometros de tronco
Dendrometros de fruto
Agua en suelo (Graficas)
Zims (graficas)

Isadora 2023 (La Hampa)

Estado BATERIAS

Baterias (Graficas)

Estación 1 (Parcela 1)

Zims (graficas)
Dendrometros (Graficas)

Estación 2 (Parcelas 2 y 3)

Zims (graficas)
Dendrometros (Graficas)

Estación 3 (Parcela 4)

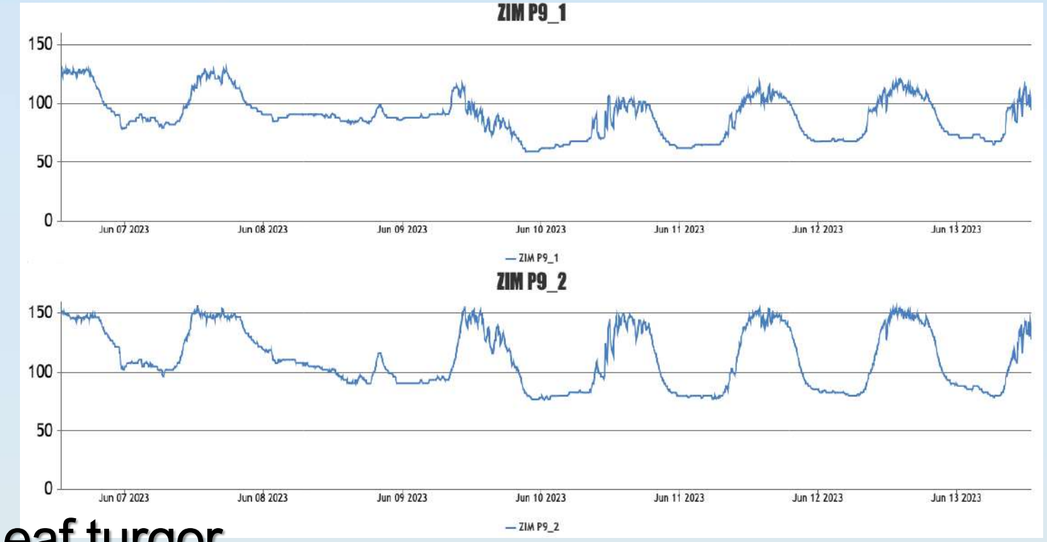
Zims (graficas)
Dendrometros (Graficas)

Estación 4 (Parcela 5 y 6)

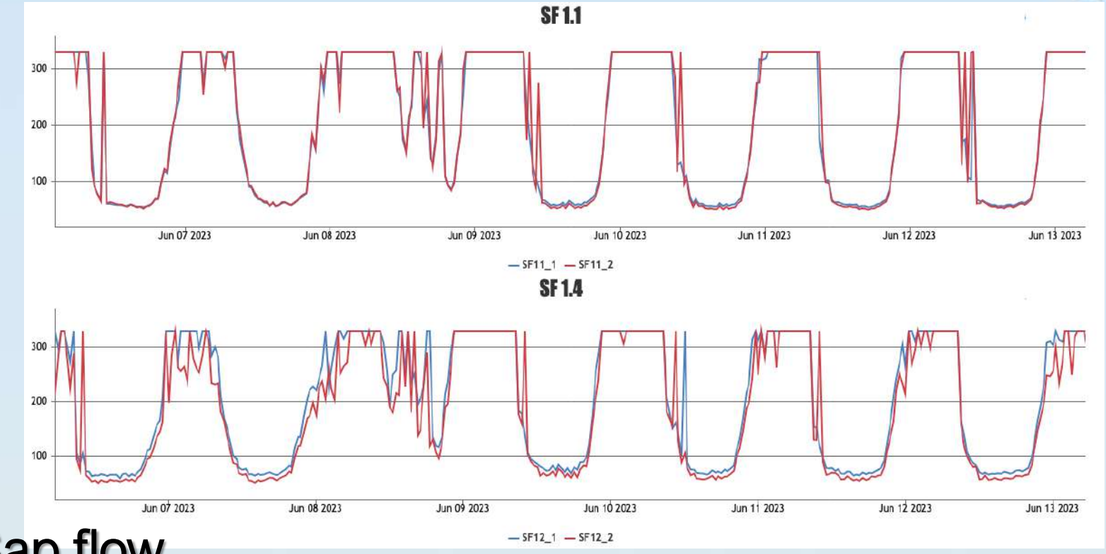
Zims (graficas)
Dendrometros (Graficas)

List of available graphs
to monitor two of our projects

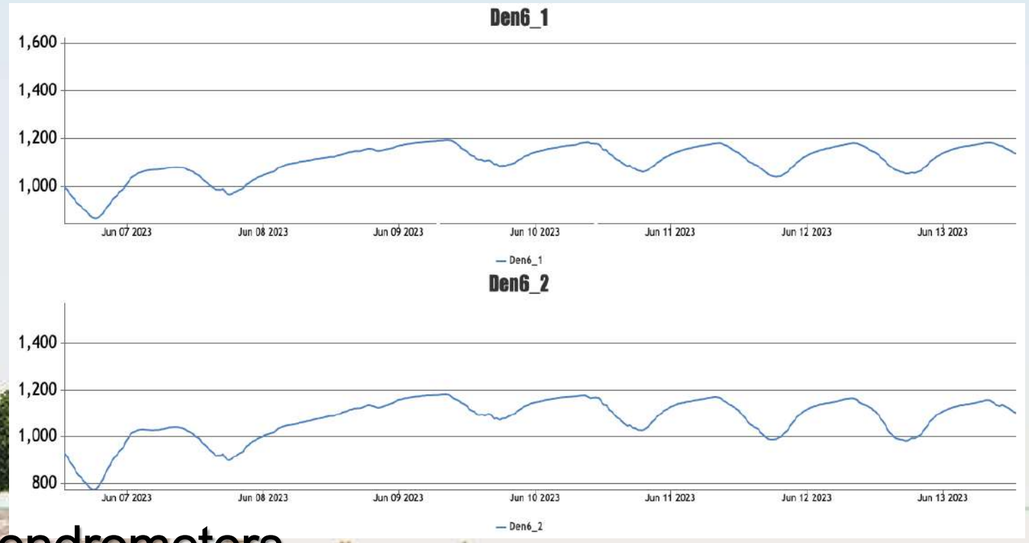
Campbell SCI Graphs



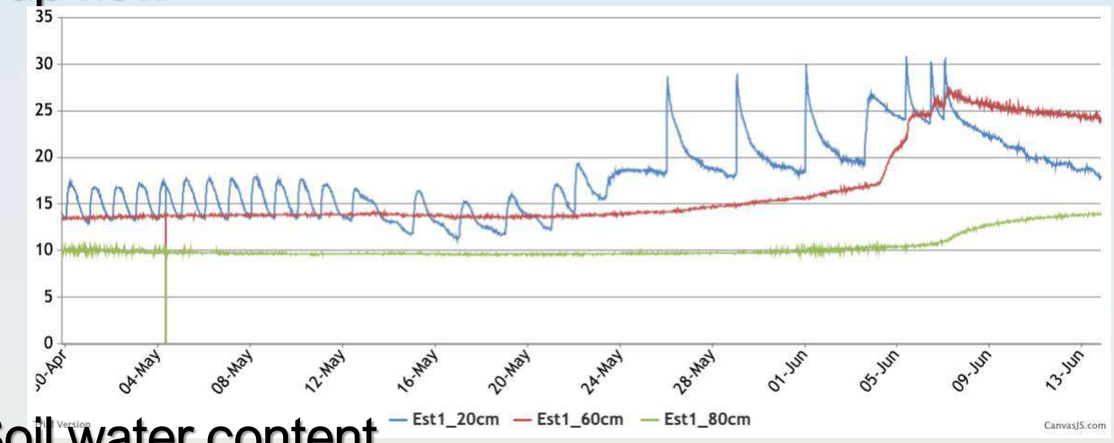
Leaf turgor



Sap flow

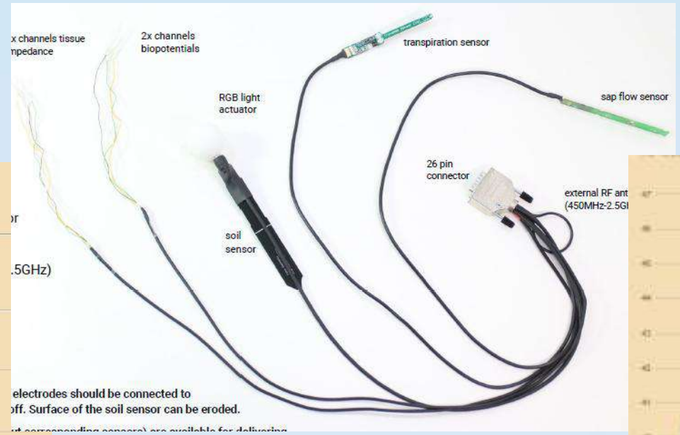


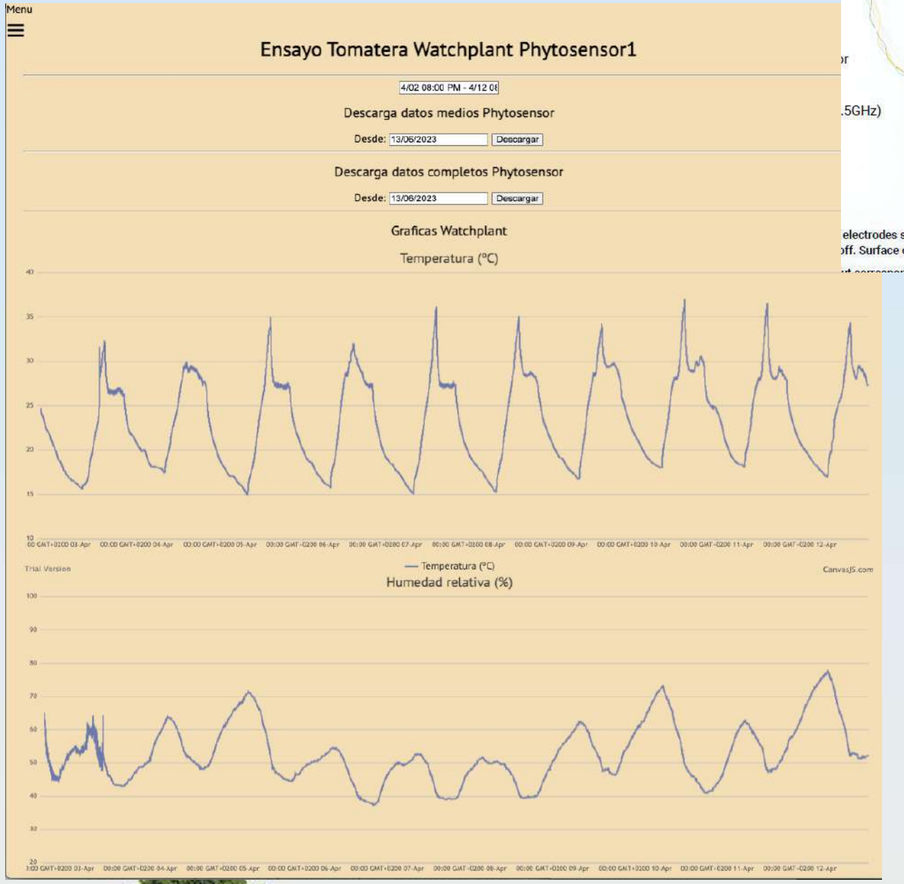
Dendrometers



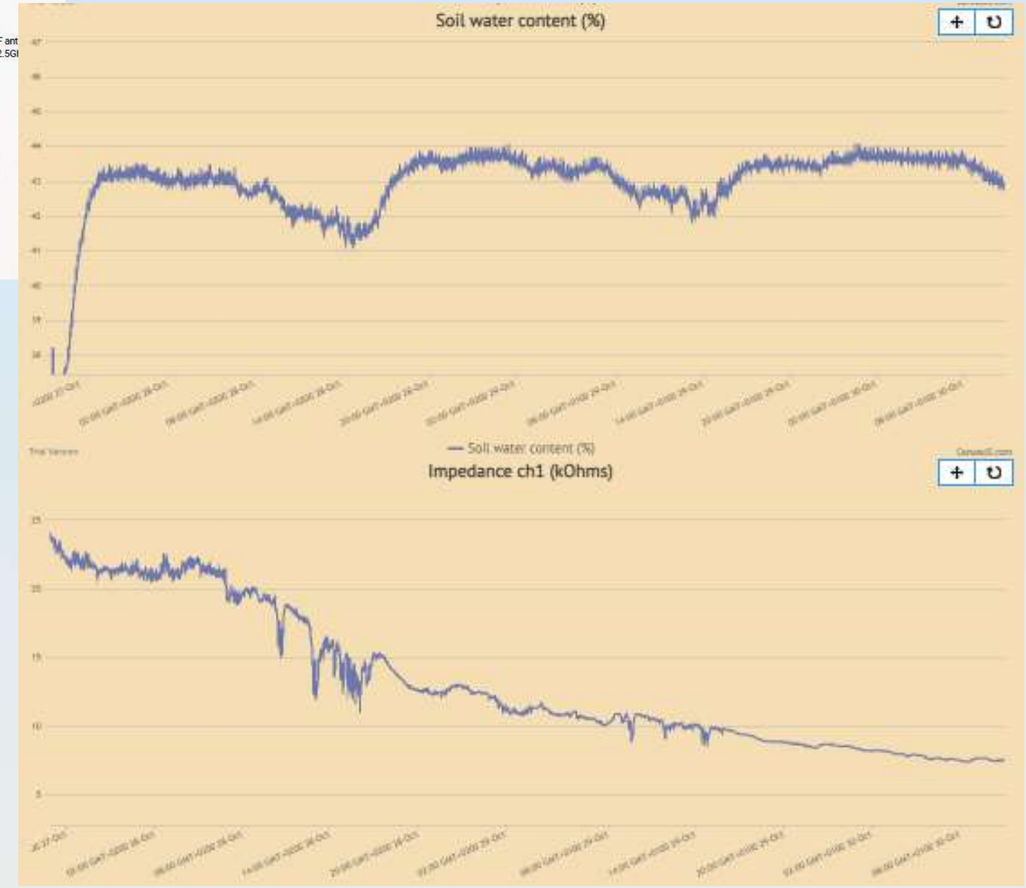
Soil water content

Phytosensor graphs

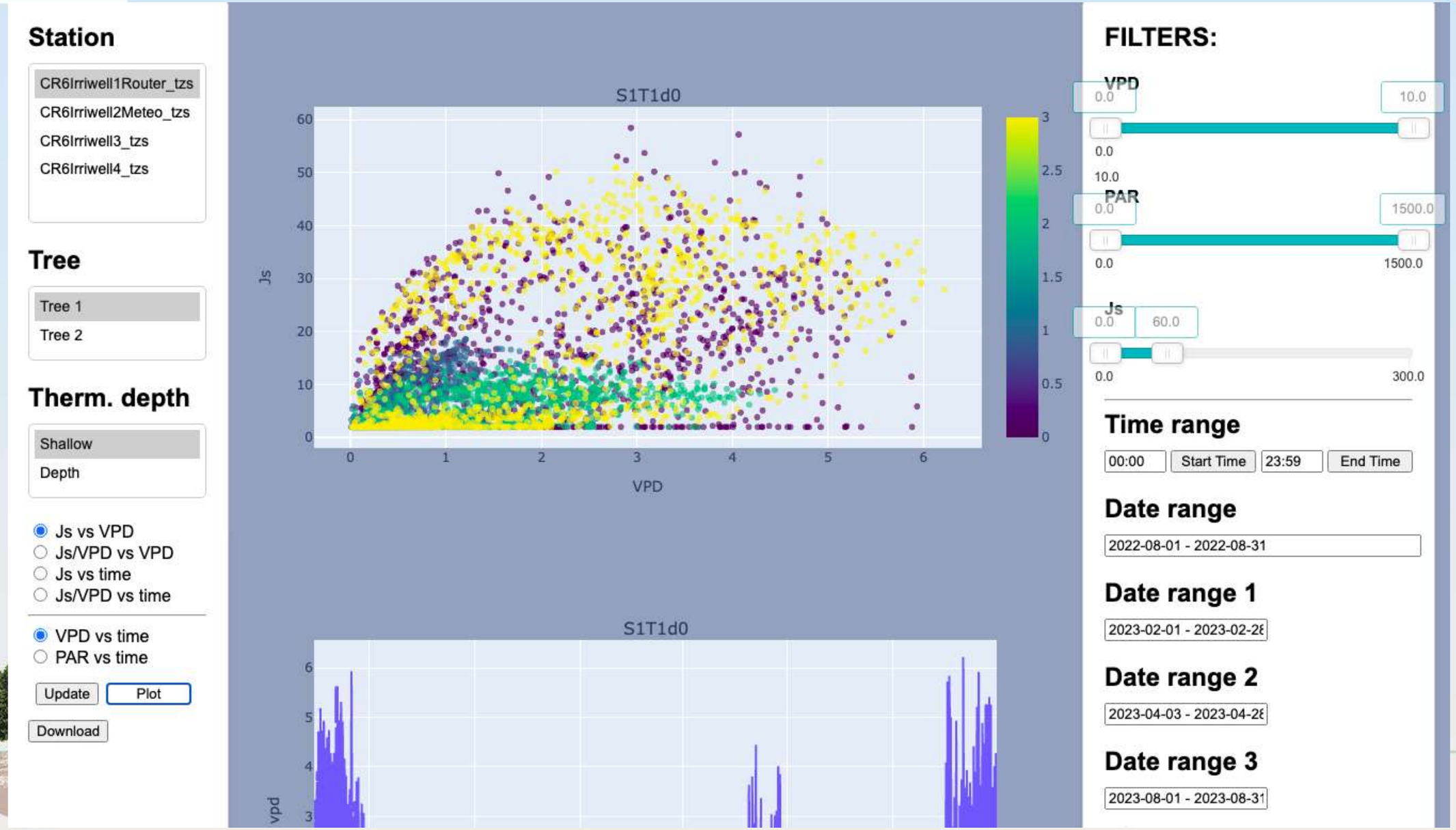








Custom web apps for data analysis



Custom web apps for data analysis

gs ANALIZER

Station

3

Tree

Tree 1

Therm. depth

Shallow

Canopy zone (gs)

Left

Measurement day

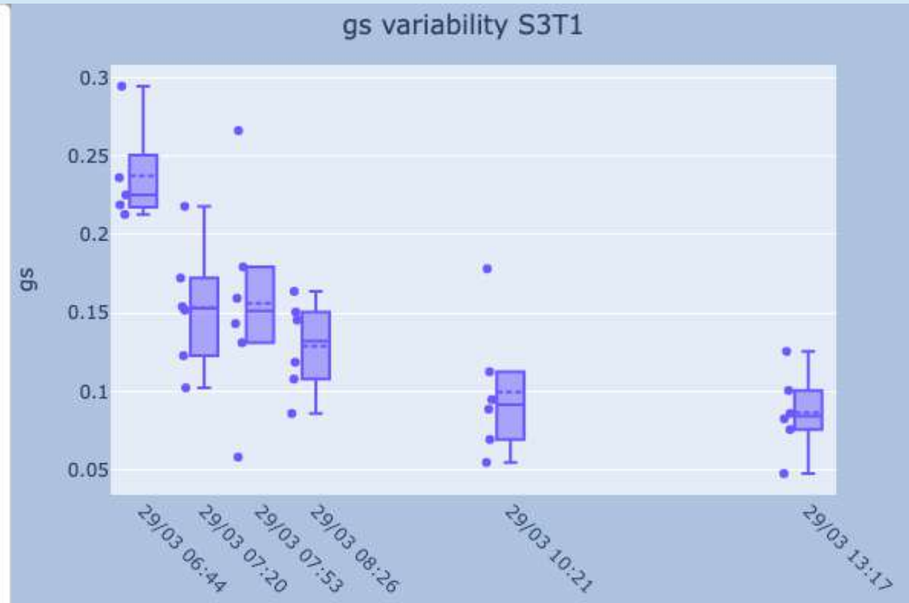
29/03/2023 Plot

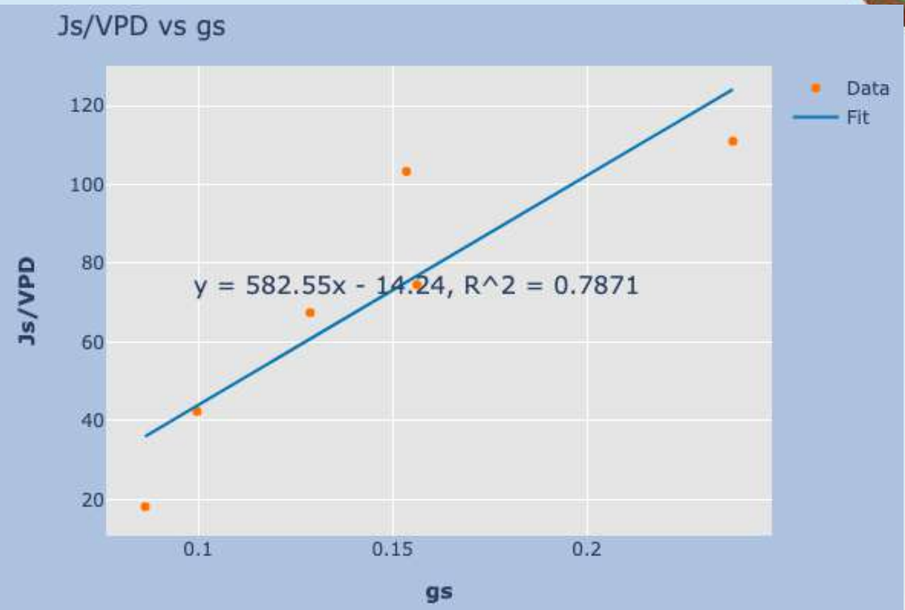
Download

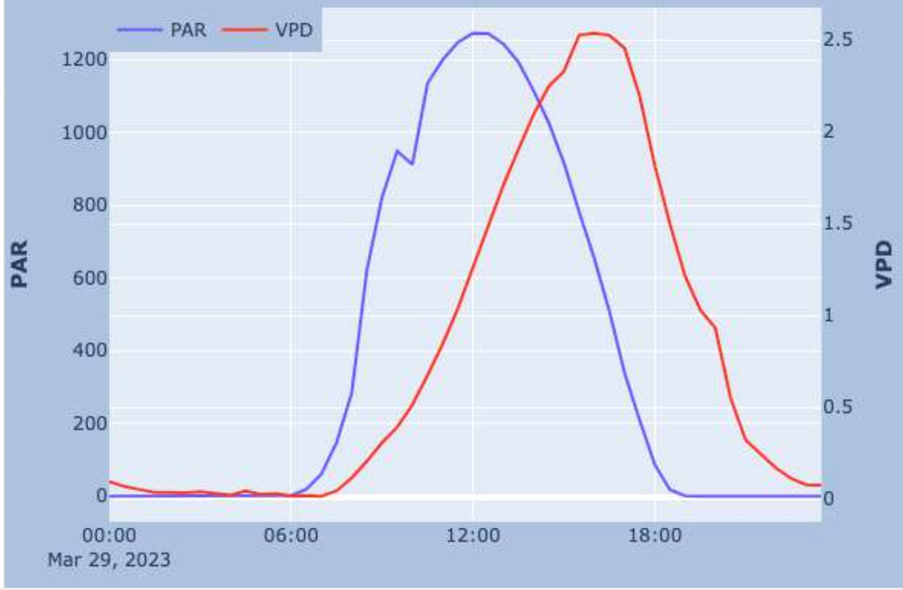
Remove points

69.0 , 2023-03-: Remove outlier

29/03 06:44 Remove round







Automatic bots for urgent alerts



crontab



Python



Telegram

rec@rec-server: /opt/recvol

```
# Each task to run has to be defined through a single line
# indicating with different fields when the task will be run
# and what command to run for the task
#
# To define the time you can provide concrete values for
# minute (m), hour (h), day of month (dom), month (mon),
# and day of week (dow) or use '*' in these fields (for 'any').
#
# Notice that tasks will be started based on the cron's system
# daemon's notion of time and timezones.
#
# Output of the crontab jobs (including errors) is sent through
# email to the user the crontab file belongs to (unless redirected).
#
# For example, you can run a backup of all your user accounts
# at 5 a.m every week with:
# 0 5 * * 1 tar -zcf /var/backups/home.tgz /home/
#
# For more information see the manual pages of crontab(5) and cron(8)
#
# m h  dom mon dow   command
*/30 * * * * python3 /opt/recvol/vigilantes/vigilante_isadora.py >> /home/rec/logisa.txt
*/30 * * * * python3 /opt/recvol/vigilantes/vigilante_irriwell.py >> /home/rec/logirr.txt
*/30 * * * * python3 /opt/recvol/vigilantes/vigilante_Bcn.py >> /home/rec/logBcn.txt
*/30 * * * * python3 /opt/recvol/vigilantes/vigilante_meteoFrutales.py >> /home/rec/logMeteoFrutales.txt
*/28 * * * * python3 /opt/recvol/vigilantes/vigilante_Invy.py >> /home/rec/logvir.txt
*/10 * * * * python3 /opt/recvol/vigilantes/vigilante_home.py >> /home/rec/loghom.txt

crontab.5gKvHs/crontab [+]                                    30,0-1        Final
```



Automatic bots



crontab



Python



Telegram

```python
def consultaActivos():
    url = 'http://gruporec.csic.es/consultaBD.php'

    # Realizar la solicitud al script PHP
    response = requests.get(url)

    # Verificar si la solicitud fue exitosa
    if response.status_code == 200:
        # Obtener los datos de la respuesta como diccionario
        data = json.loads(response.text)

        # Crear un diccionario con clave=vigilante y valor=activo
        vigilantes = {item['vigilante']: item['activo'] for item in data}

        # Imprimir el diccionario resultante
        print(vigilantes)
        return(vigilantes)
    else:
        # La solicitud no fue exitosa, mostrar el mensaje de error
        print('Error al realizar la solicitud:', response.status_code)

vigilantes=consultaActivos()
for station in urls:
    if vigilantes[station]:
        sftpFolder=urls[station]
        sensors=["phy1","phy2","phy3","phy4"]
        sftpSubFolders=[x for x in sensors if x not in omitted[station]]
        print(sftpSubFolders)
        checkEstacion(url_base=url_base,sftpFolder=sftpFolder,sftpSubFolders=sftpSubFolders)

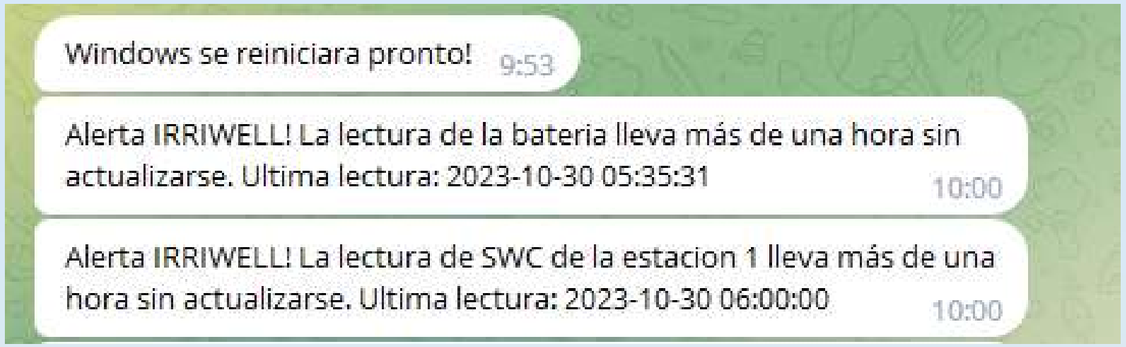
#Comprobacion general funcionamiento vigilante. Si funciona enviará cada día un mensaje, a las 19:30h, con el estado de las baterias
now=datetime.now()
if (now.hour==8 and now.minute<30):
  print("Programador BCN ok!")
  send_message(1114832641, "Vigilante BCN OK.")
```

Automatic bots

crontab

Python

Telegram





Automatic bots

Configuración de Vigilantes

Lista de Vigilantes

- [ ] Inv_IRNAS
- [x] Irriwell1
- [x] Irriwell2
- [x] Irriwell3
- [x] Irriwell4
- [ ] Isadora1
- [ ] Isadora2
- [ ] Isadora3
- [ ] Isadora4
- [ ] Isadora5
- [ ] Isadora6
- [x] CR6_11577Kaki
- [x] DIGI_ALM1_L_9682
- [x] DIGI_ALM2_C_11669
- [x] DIGI_LIM1_P7_9683
- [x] DIGI_LIM2_P8_11239
- [x] DIGI_OLI1_P19_9680
- [x] DIGI_OLI2_P20_8786
- [x] WatchplantIDAEA
- [ ] WatchplantEIXAMPLE
- [x] WatchplantVIC
- [x] homeLuz

Guardar configuración

Bots can be enabled/disabled through a web page



Heat transfer computer simulation

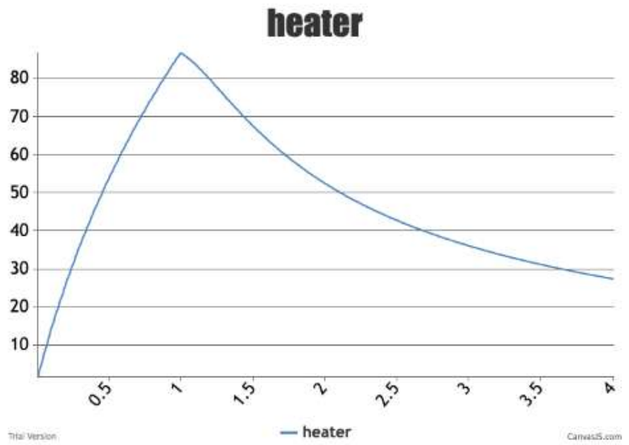
Parametros de configuracion

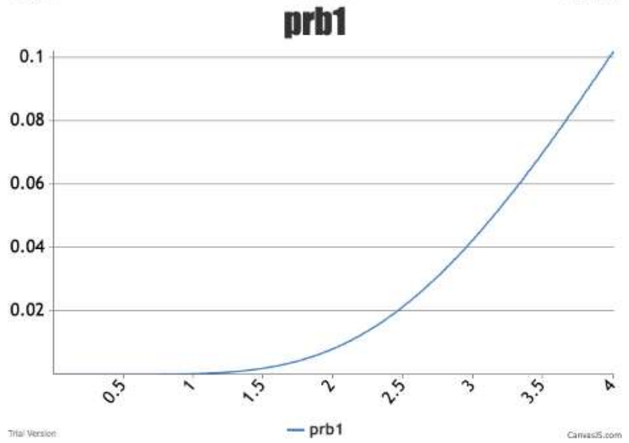
Iniciar simulación | Guardar cambios | Recuperar parametros por defecto

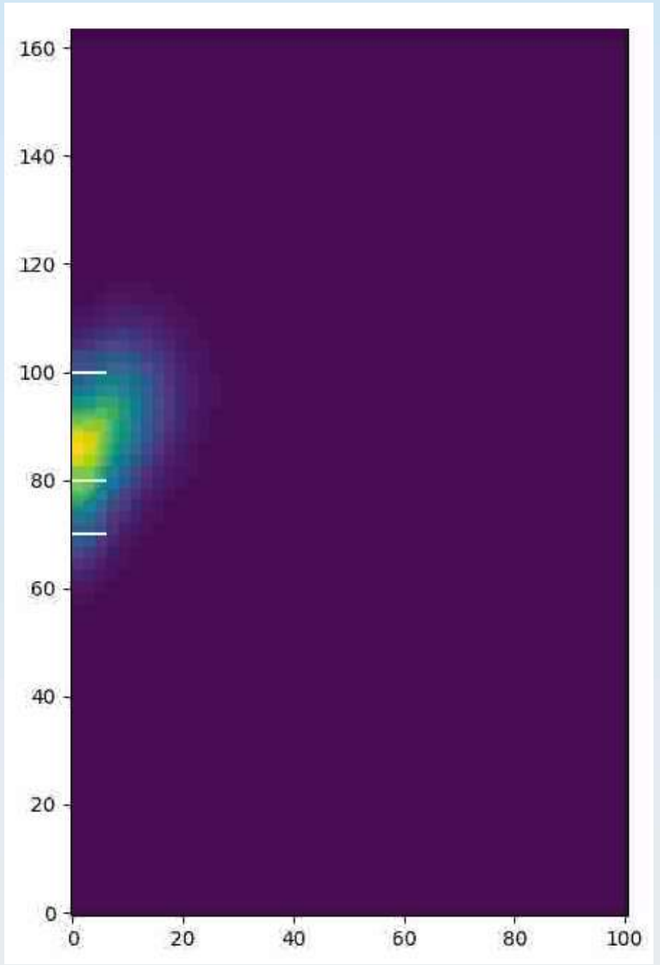
Parametros

XLEN	0.0817
DX	0.0005
YLEN	0.04
DY	0.0004
TLEN	4
DXPRB1	-0.05
DYPRB1	0
DXPRB2	0.01
DYPRB2	0
DXPRB3	0.08
DYPRB3	0
QHTR	65
RPRB1	0.0008
RPRB2	0.0008
RPRB3	0
XHTR	0.04
RHTR	0.0008
LHTR	0.06
LAMHTR	141
RHOHTR	5870
CHTHTR	640
LAMPRB	8.5
RHOPRB	2660
CHTPRB	908
rhob	550
imf	

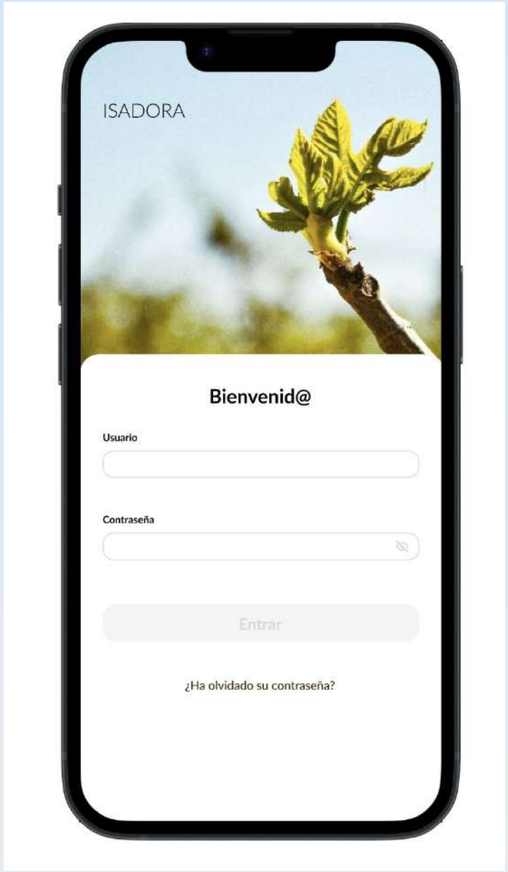
Graficas



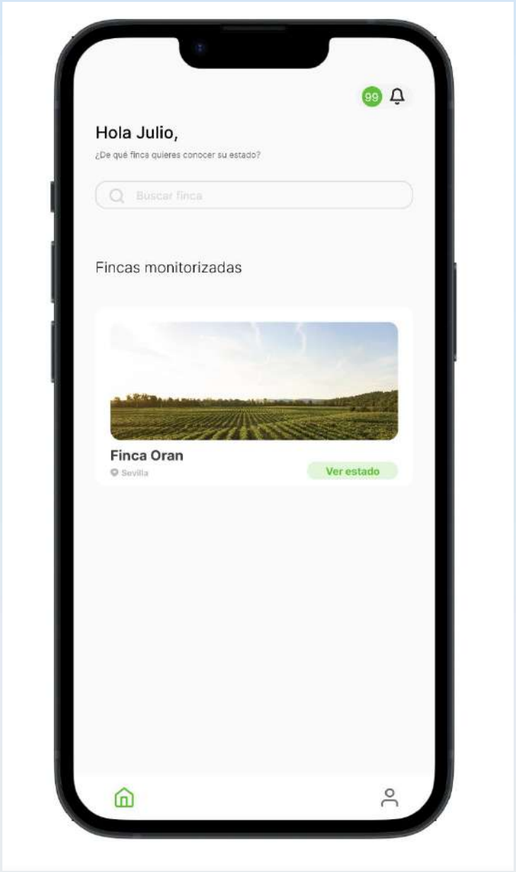




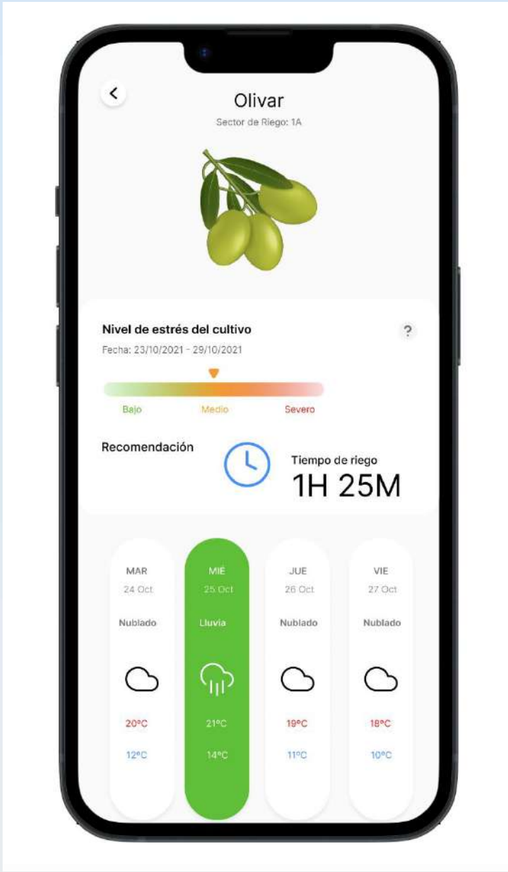
Irrigation Apps



User login



Select farm/crop



Weather forecast and
Irrigation recommendation

Behind the scenes



DATABASES

HTML + CSS + Vanilla JavaScript

VUE

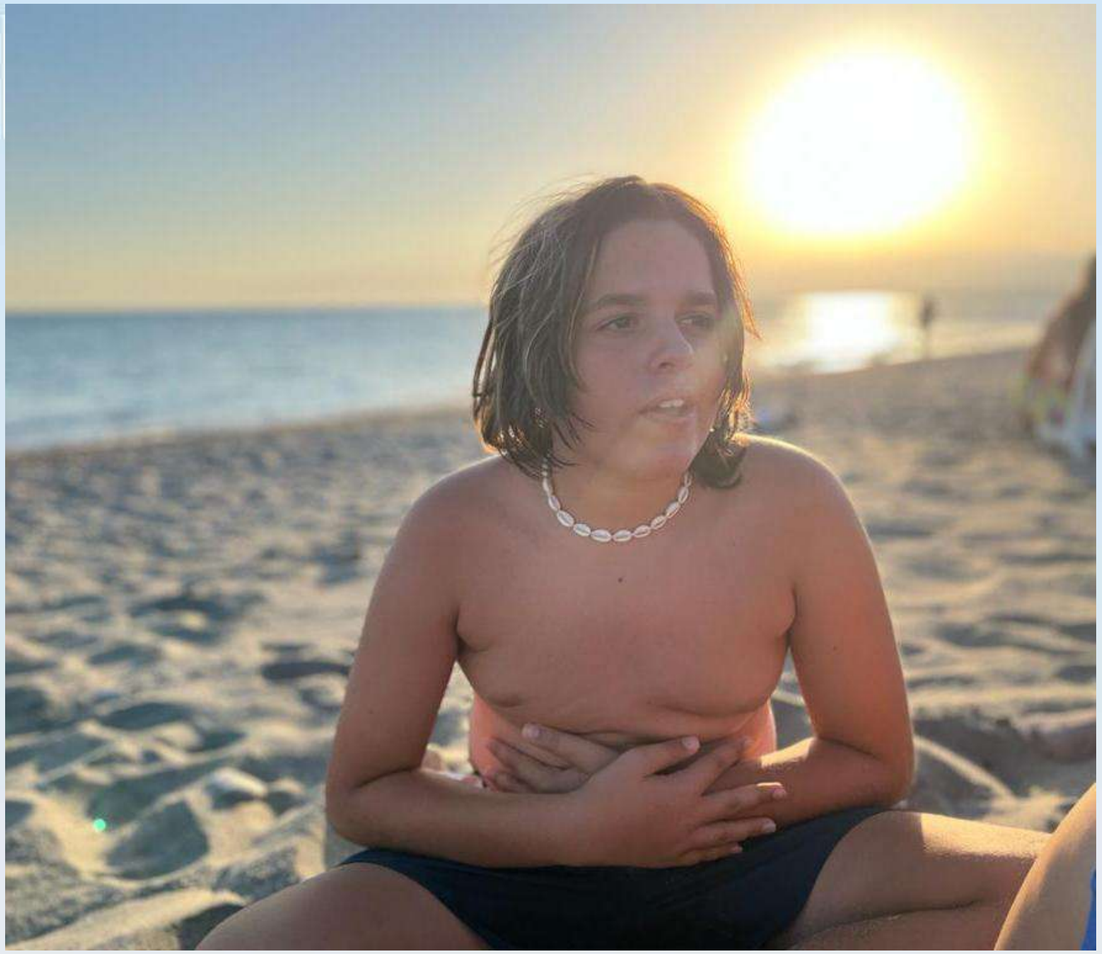
Thank you!



Grupo de Riego y Ecofisiología de Cultivos
Grupo REC
www.irnas.csic.es/rec

Terra vita est

@rr4v
rafaelromerovicente@gmail.com
Rafael Romero



HÉCTOR



OLIVIA

The ISADORA Project

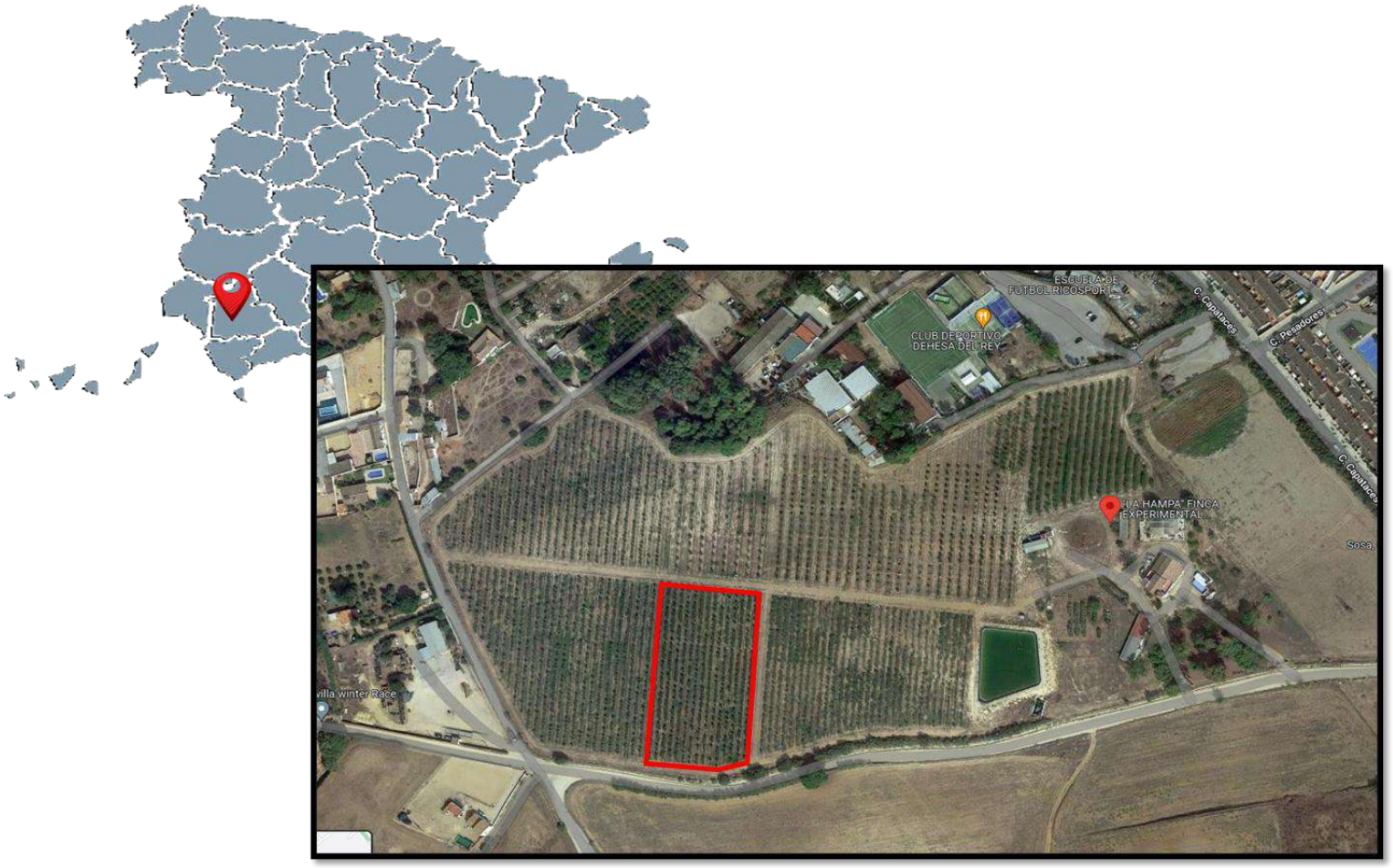


J.E. (Enrique) Fernández

Institute for Natural Resources and Agrobiology (IRNAS)
Plant Ecophysiology and Irrigation group
Spanish National Research Council (CSIC)

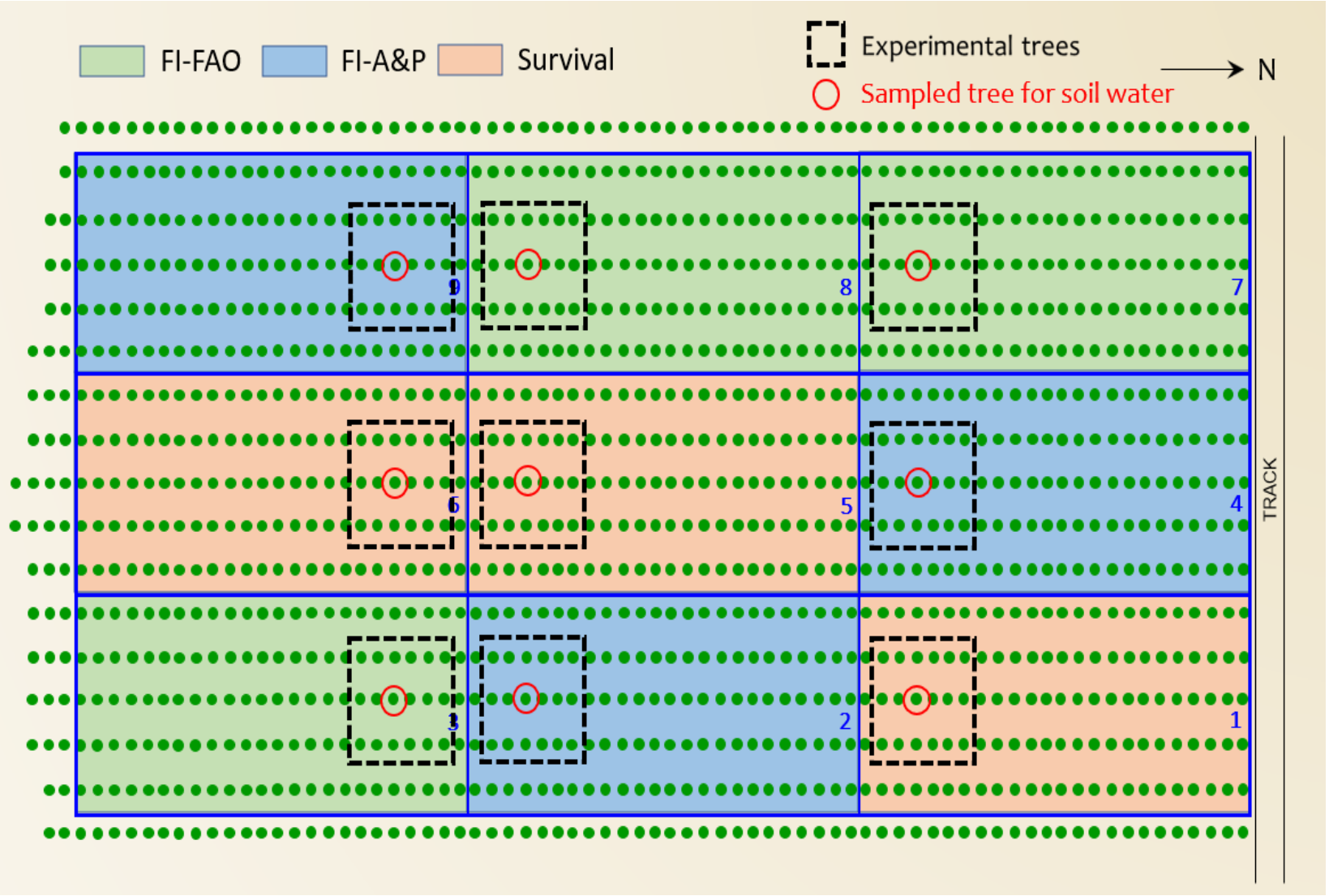
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The experimental orchard



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Three treatments in a Randomized Block Design



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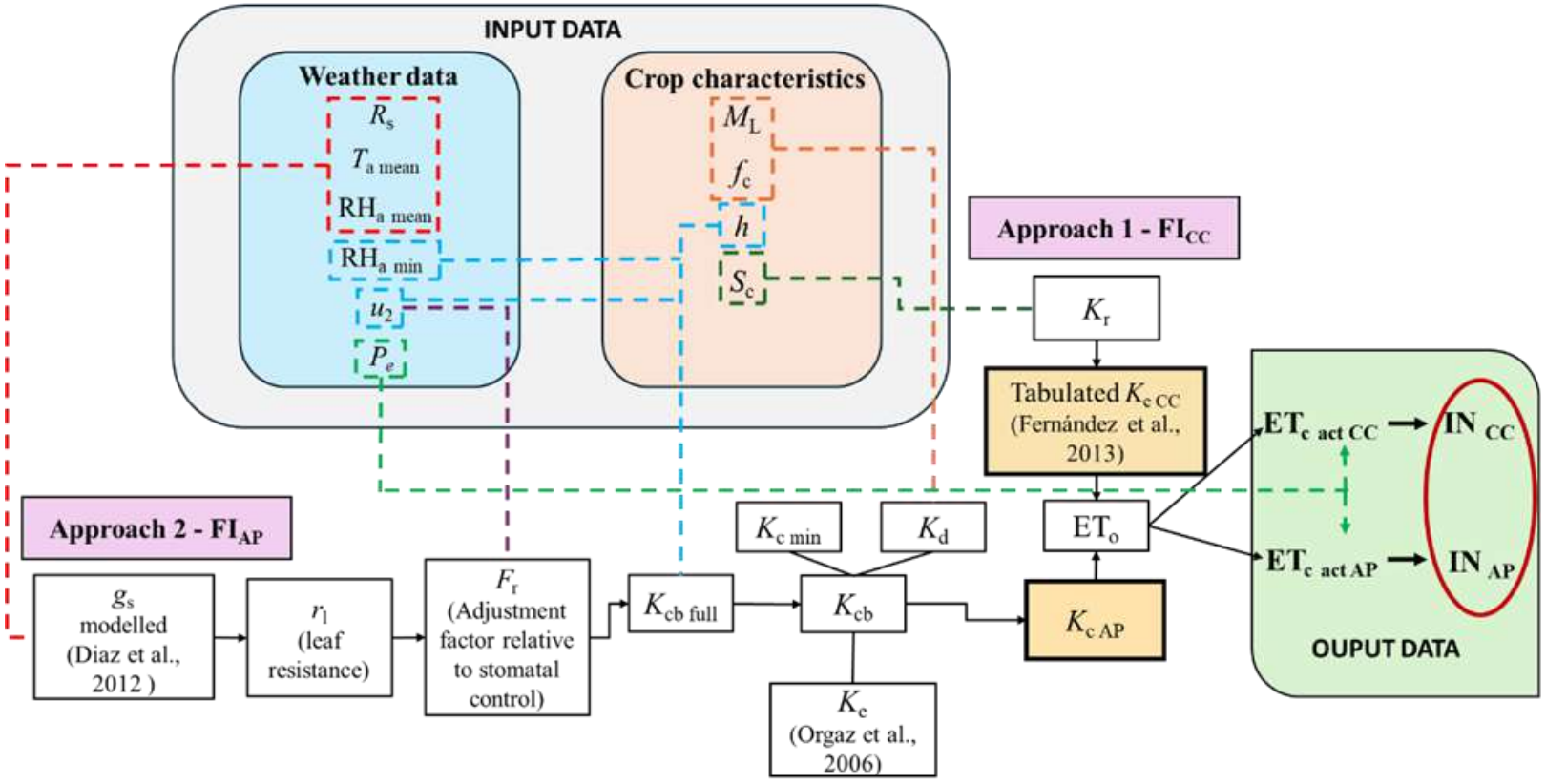
Measurements

- Meteorological variables
- Soil water content
- Leaf water potential
- Stomatal conductance
- Net photosynthesis
- Trunk diameter variations
- Leaf turgor
- Shoot growth & No. Internodes
- Hedge height & width
- Fruit and oil yields



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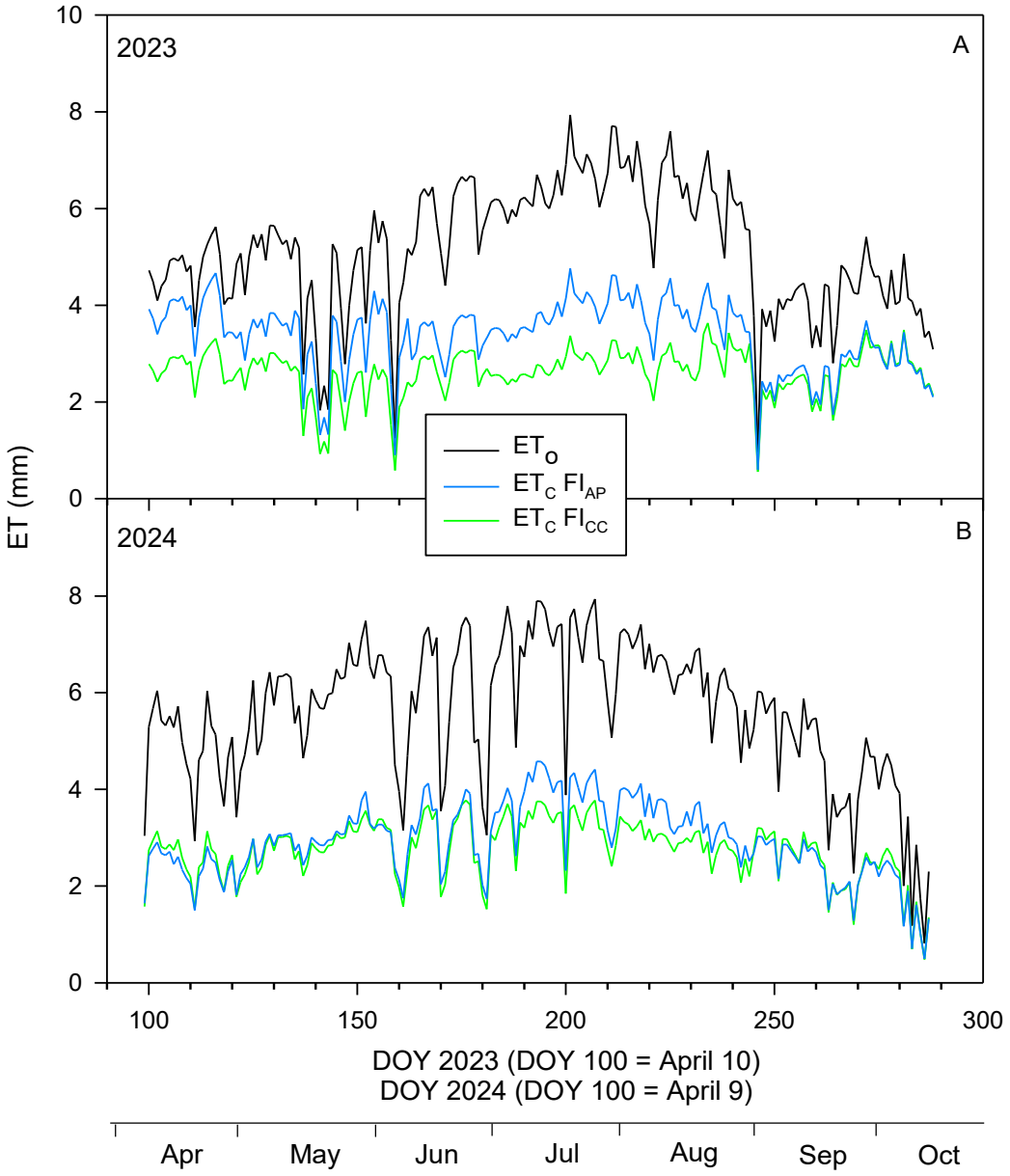
Comparisson Kc vs. A&P



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Results

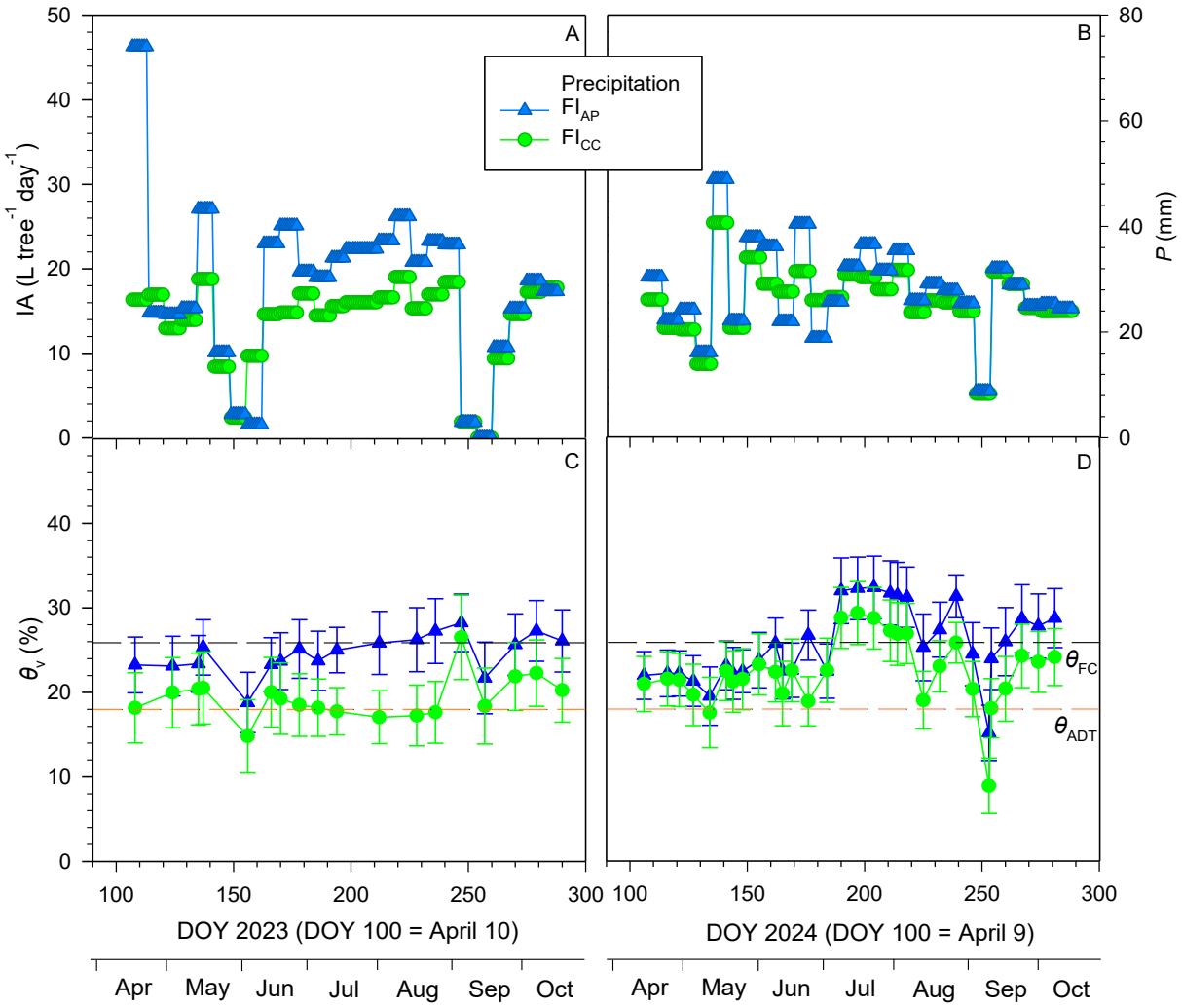
Seasonal courses of the FAO56 Penman-Monteith reference evapotranspiration (ET_o) determined from records at *La Hampa* weather station, for the two experimental seasons. Also shown is the calculated crop evapotranspiration (ET_c) for each irrigation treatment. DOY = Day of year.



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Results

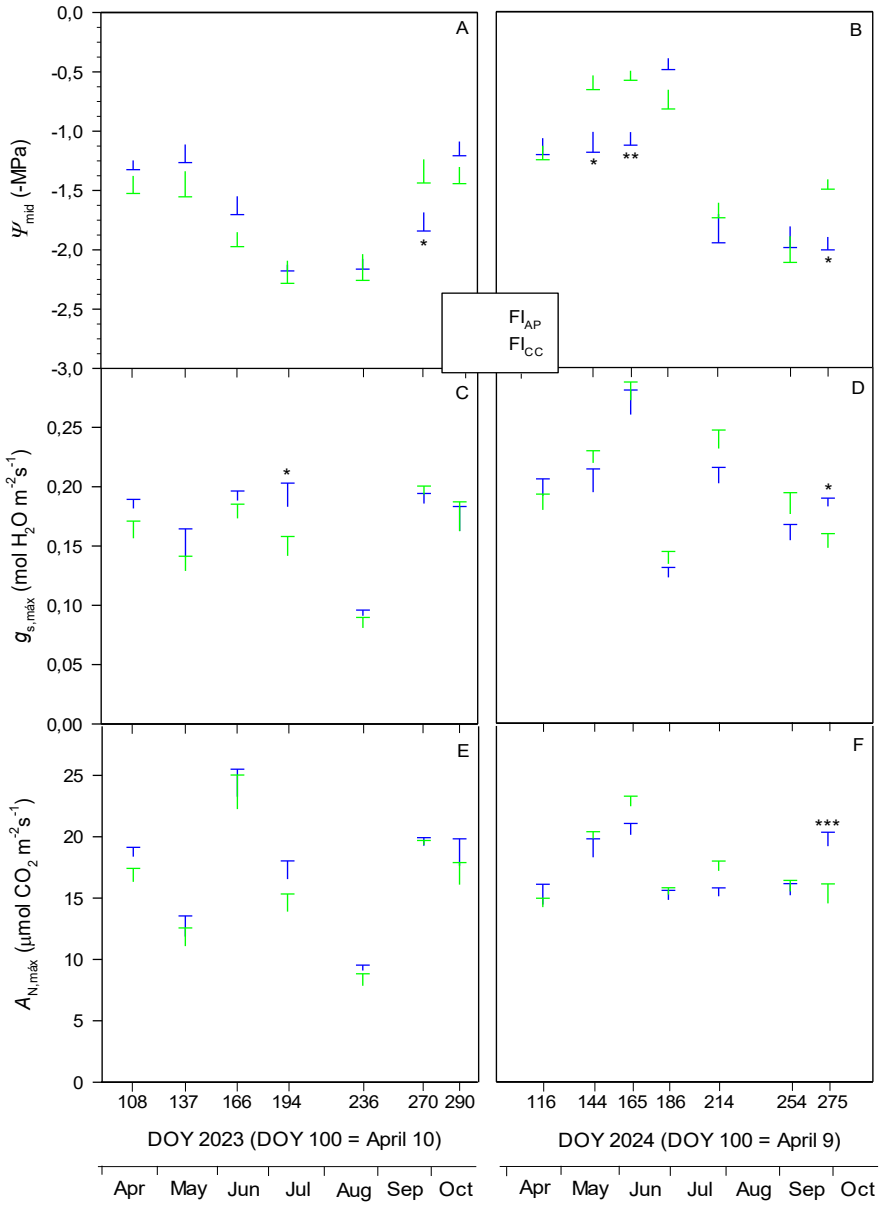
Seasonal courses of both the irrigation amounts (IA) supplied to each treatment and the recorded precipitation (*P*) for both irrigation seasons (A,B). Also shown are the seasonal courses of the volumetric soil water contents (ϑ_v, avg ± SE) in the soil of both treatments (C,D). ϑ_{FC} and ϑ_{ADT} are the volumetric soil water contents at field capacity and at the allowable depletion threshold. No significant differences were found between treatments for the volumetric soil water contents. DOY = Day of year.



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Results

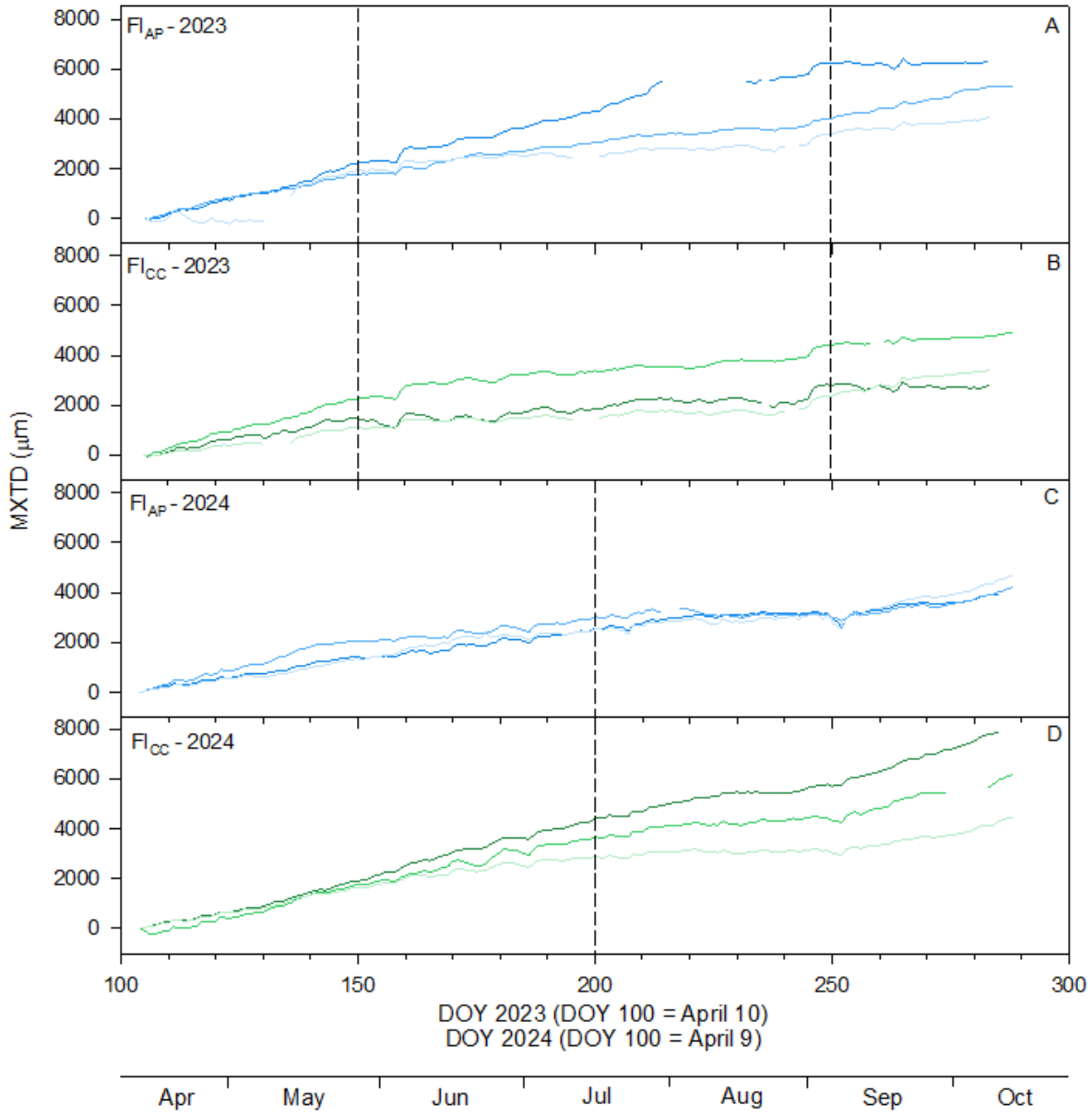
Seasonal courses of midday leaf water potential (Ψ_{mid}) (A,B), daily maximum stomatal conductance ($g_{s,max}$) (C,D) and daily maximum net photosynthesis ($A_{N,max}$) (E,F) recorded in trees of both irrigation treatments along the two experimental seasons. Values are avg ± SE; *, ** and *** indicates statistically significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. DOY = Day of year.



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Results

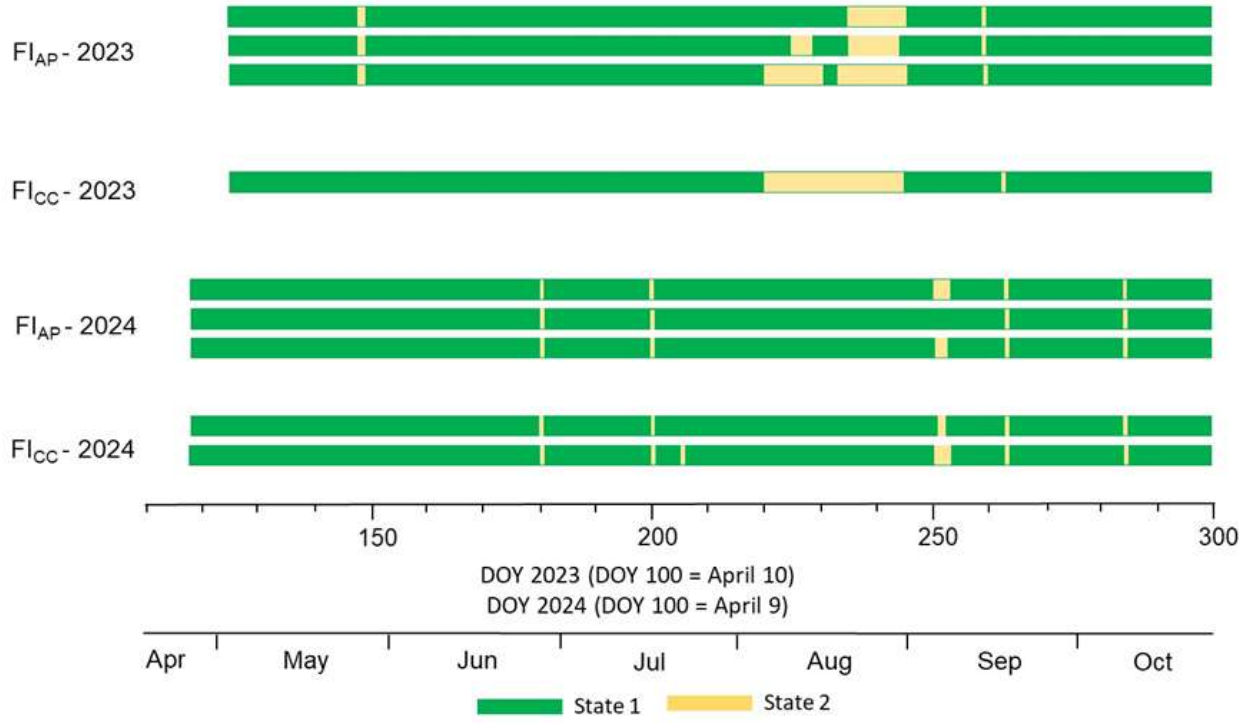
Seasonal courses of the maximum daily trunk diameter (MXTD) recorded in three representative trees of each treatment and experimental season. The dashed lines show the periods of greater water stress (in between the two lines for 2023 and to the right of the line in 2024).



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Results

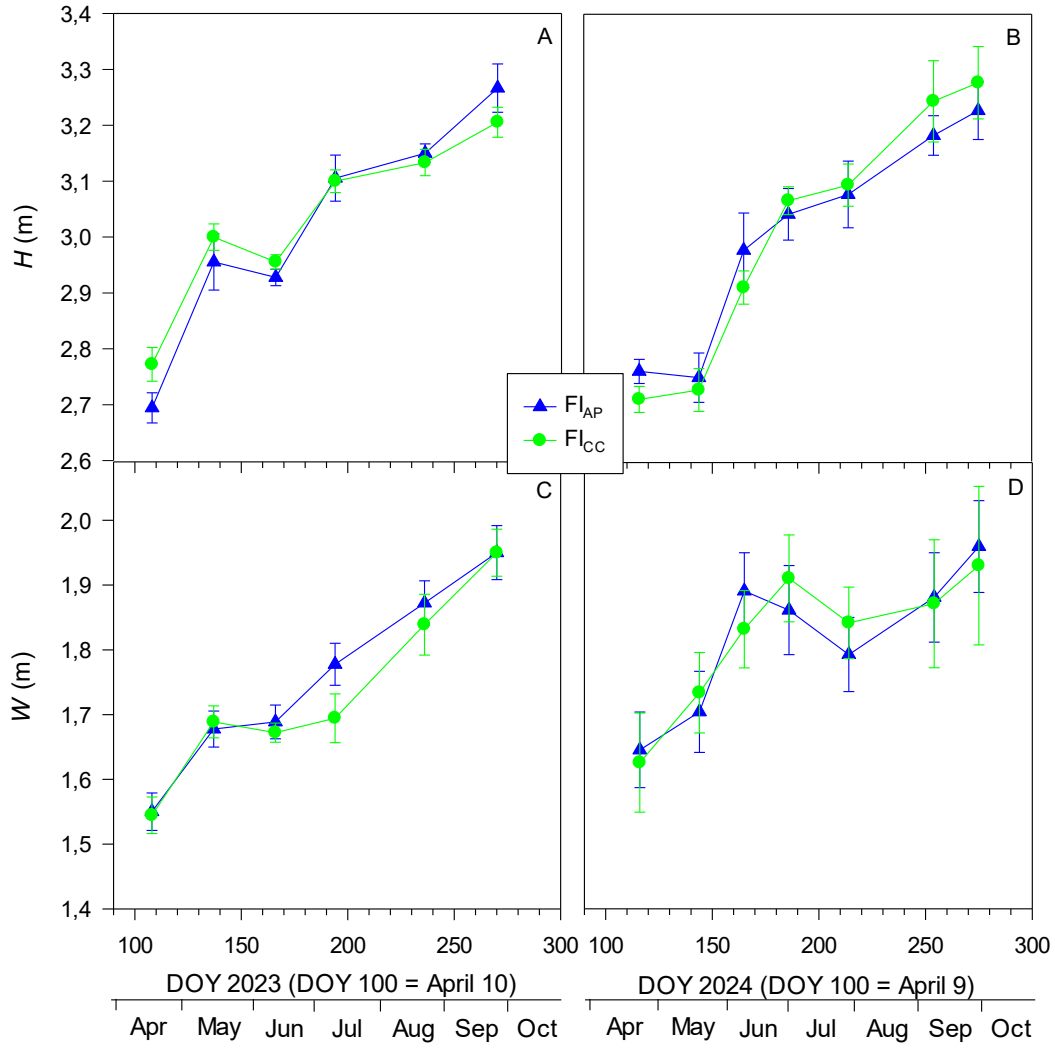
Seasonal courses of the states of turgescence of leaves from the two treatments and experimental seasons. We installed six ZIM probes per treatment and all of them showed State 1, except those shown here.



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Results

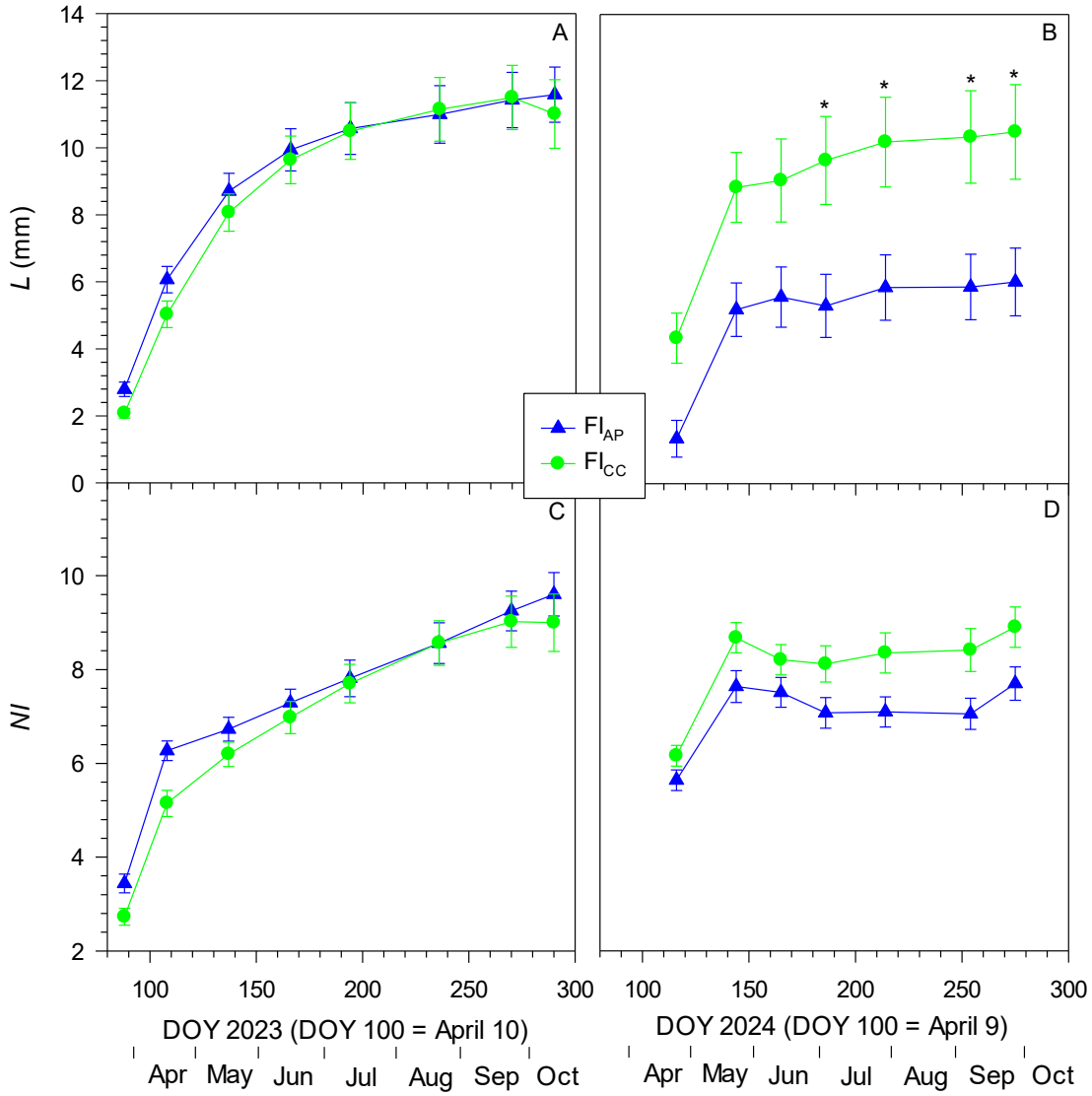
Seasonal courses of the height (*H*) and width (*W*) of the hedges of each treatment and experimental season. Values are avg ± SE. No significant differences between treatments were found. DOY = Day of year.



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Results

Seasonal courses of the length (*L*) and number of internodes (*NI*) of shoots of the current year, for each treatment and experimental season. Values are avg ± SE; * indicates statistically significant differences at $p < 0.05$. DOY = Day of year.



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Results

Table 1. Monthly values of both the coefficient related to the percentage of ground covered by the crop (K_r), determined for the two experimental irrigation seasons, and the crop coefficient (K_c) used to estimate the irrigation needs in the FI_{CC} treatment.

Month	K_r 2023	K_r 2024	K_c
April	0.62	0.69	0.76
May	0.74	0.70	0.68
June	0.73	0.79	0.63
July	0.75	0.84	0.57
August	0.89	0.80	0.57
September	1.00	0.82	0.65
October	1.00	0.85	0.69

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Results

Table 2. Monthly values of the crop coefficient (K_c) determined for the two experimental irrigation seasons and used to estimate the irrigation needs in the FI_{CC} and FI_{AP} treatment.

	2023		2024		
Treatment	FI $_{CC}$	FI $_{AP}$	FI $_{CC}$	FI $_{AP}$	FI $_{AP}$
Month	$K_{c\ CC}$	$K_{c\ AP}$ w/ Tab F_r	$K_{c\ CC}$	$K_{c\ AP}$ w/ Tab F_r	$K_{c\ AP_adj}$ w/ Adj F_r
April	0.47	0.83	0.52	0.51	0.49
May	0.50	0.72	0.48	0.56	0.50
June	0.46	0.57	0.50	0.59	0.53
July	0.43	0.60	0.48	0.61	0.56
August	0.51	0.62	0.46	0.58	0.53
September	0.65	0.68	0.53	0.58	0.52
October	0.69	0.67	0.59	0.58	0.56

Tab F_r – Tabulated values from Pereira et al. (2021); Adj F_r – adjusted values using the enhanced leaf resistance values.

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Results

Table 3. Parameters used for the sensitivity analysis described in Section 2.2. $K_{cb\ mid}$ = basal crop coefficient for the mid-season stage; IN = Irrigation needs; f_c = fraction of ground cover; h = tree height; r_l = leaf resistance; r_{typ} = typical leaf resistance of a given crop; M_L = multiplier describing the effect of canopy density on shading the ground; Values in bold are the observed/used values in the 2023 season.

Affected variable	Changed variables													
	f_c			h			r_l			r_{typ}			M_L	
	0.41	**0.46**	0.51	2.70	**3.00**	3.30	120	290	**460**	**100**	180	260	1.30	**1.50**
$K_{cb\ mid}$	0.51	**0.56**	0.62	0.56	**0.56**	0.56	0.89	0.69	**0.56**	**0.56**	0.72	0.81	0.49	**0.56**
IN (mm)	522	**543**	569	543	**543**	544	685	600	**543**	**543**	613	651	515	**543**

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Results

Table 4. Results from the analysis of leaf nutrient content conducted for each irrigation treatment and experimental year.

	2023		2024		
Element (unit)	FI_{AP}	FI_{CC}	FI_{AP}	FI_{CC}	Optimum levels
N (%)	2.02	1.92	2.05	2.11	1.50 - 2.00 (1.3 - 1.7)
P (%)	0.17	0.17	0.20	0.21	0.09 - 0.15
K (%)	1.27	1.29	1.26	1.28	0.80 – 1.00
Ca (%)	1.11	1.17	0.93	0..9	1.00 – 2.50
Mg (%)	0.26	0.27	0.22	0.22	0.10 – 0.40
Mn (mg kg^{-1})	24.67	22.04	25.32	20.93	20 - 90
Zn (mg kg^{-1})	10.96	11.12	14.06	14.77	10 - 60
Cu (mg kg^{-1})	13.42	14.07	7.98	11.68	5 - 120
B (mg kg^{-1})	32.96	32.30	32.48	33.02	18 - 150
Fe (mg kg^{-1})	62.25	71.76	49.11	44.36	80 -150
Na (%)	0.08	0.06	0.06	0.06	< 0.05

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Results

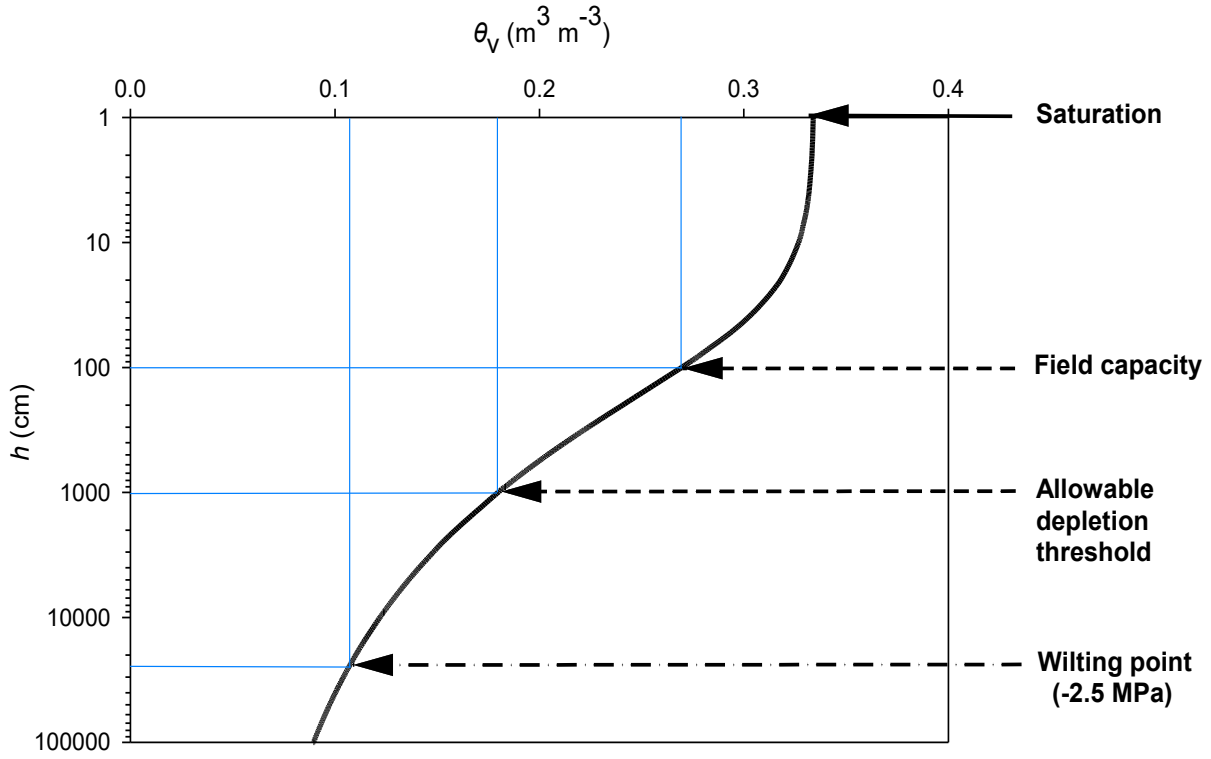
Table 5. Fruit and oil yields recorded for each year and treatment. Also shown are the total oil content estimated by nuclear magnetic resonance (NMR), the oil extracted using the Abencor method, and extractability. In 2023, oil yield was not determined. Values are avg ± SE. No significant differences were observed between treatments.

Year	Treatment	Fruit yield (kg ha^{-1})	Oil yield (kg ha^{-1})	Oil content (%)		Extractability (%)
				NMR	Abencor	
2023	FI_{cc}	27320.7 ± 3583.9 a	-	-	-	-
	FI_{AP}	20420.8 ± 2349.3 a	-	-	-	-
2024	FI_{cc}	16608.9 ± 3307.5 a	1215.9 ± 242.6 a	13.7 ± 0.7 a	7.3 ± 0.4 a	57.7 ± 4.7 a
	FI_{AP}	19542.8 ± 1085.7 a	1501.8 ± 122.2 a	14.2 ± 0.3 a	7.7 ± 0.2 a	61.4 ± 7.4 a

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Results

Water retention curve calculated with the Rosetta pedotransfer function and textural values measured in the orchard. For olive, the wilting point is considered at a soil matric potential of -2.5 MPa. ϑ_v = volumetric soil water content; *h* = suction.



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Results

Table SP2. Monthly values, for the two experimental seasons, of the fraction of ground covered by the canopies of the trees of the experimental orchard, determined according to both Approach 1 (S_c) and Approach 2 (f_c) (see Section 2.2 for details). Also shown are the values of the dual crop coefficient determined with Approach 2, for both S_c values (K_{cb_Sc}) and f_c values (K_{cb_fc}). The K_{cb} values were calculated for the 2004 season, after refining the leaf resistance values as commented in Section 2.2.

	2023		2024			
Month	S_c	f_c	S_c	f_c	K_{cb_Sc}	K_{cb_fc}
April	0,31	0.39	0.35	0.39	0.38	0.42
May	0.37	0.42	0.35	0.41	0.39	0.45
June	0.37	0.42	0.40	0.44	0.43	0.48
July	0.38	0.45	0.42	0.44	0.47	0.49
August	0.45	0.47	0.40	0.43	0.44	0.47
September	0.50	0.49	0.41	0.44	0.43	0.46
October	0.50	0.39	0.43	0.46	0.44	0.47

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The ISADORA+

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The Socio-Economic analysis

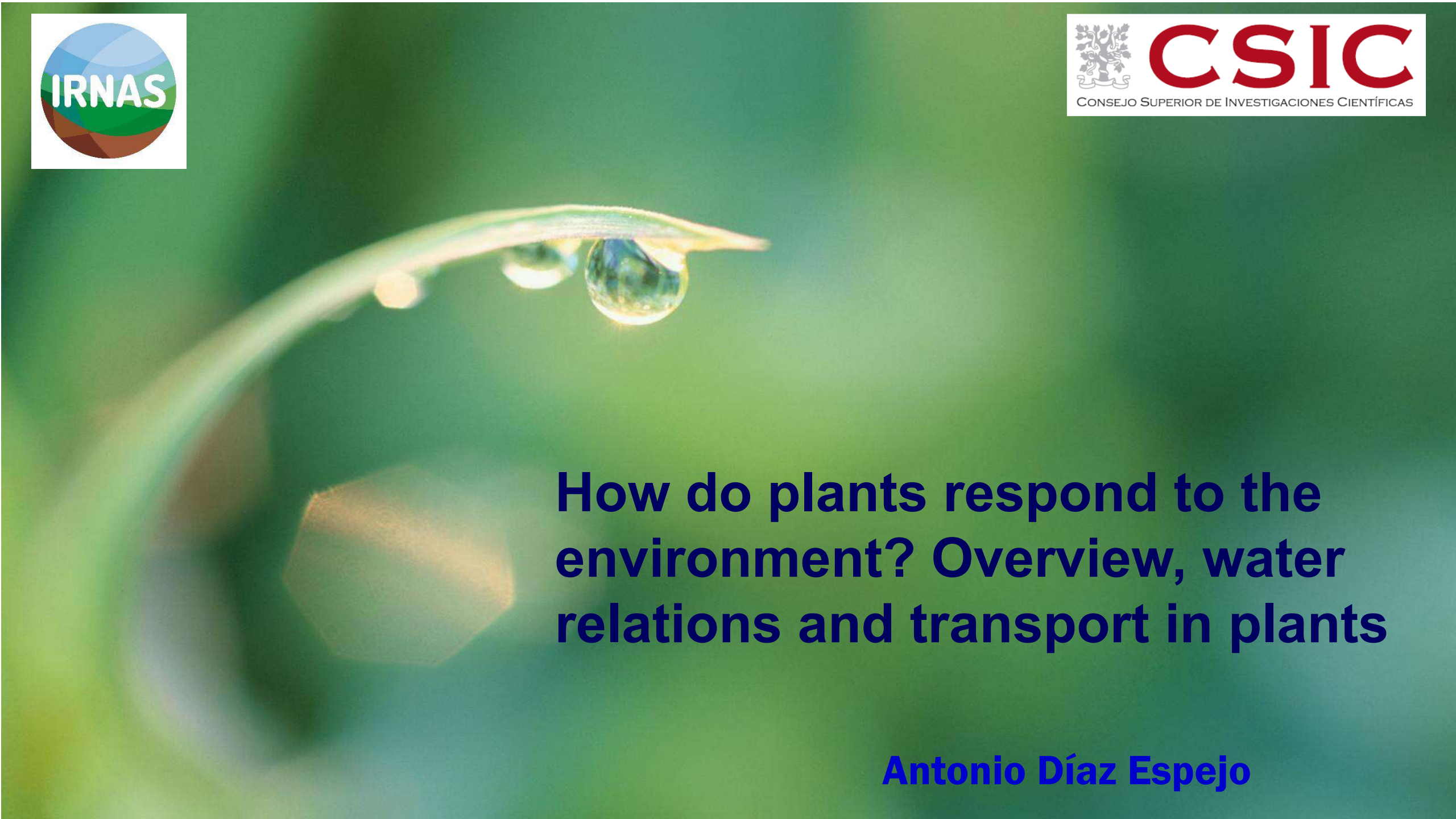
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The Ecophyisiology and Crop Irrigation (ECOVER) group

Institute for Natural Resources and Agrobiology (IRNAS)
Spanish National Research Council (CSIC)

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How do plants respond to the environment? Overview, water relations and transport in plants

Antonio Díaz Espejo

la cuadratura del círculo

¿Y si las plantas hablaran?

Las plantas notan que les falta agua para continuar su actividad, bien por falta de agua en suelo o por condiciones meteorológicas desfavorables, y generan unas señales que podemos medir de forma automática y contínua y monitorizar, ya sea con el PC de nuestra oficina o con nuestro smartphone.

Antonio Díaz Espejo - Instituto de Recursos Naturales y Agrobiología (IRNAS/CSIC)

22/01/2015 - 22:37h

Compartir 19 Me gusta Twittear 10



Main objectives

- *To understand how plants react to the environment*
- *Physiological mechanisms of response to the environment*
- *Limitations in the response to water stress*
- *How can we use the ecophysiological knowledge in precision agriculture*

Plants and their environments





How cactus are able to survive in deserts?

How different are their physiological mechanisms in comparison with plants of a riparian habitat?

Why cannot we find cactus in the riparian site?

Crops and their environments





What limits the growth of kiwis in central regions of Spain or Portugal?

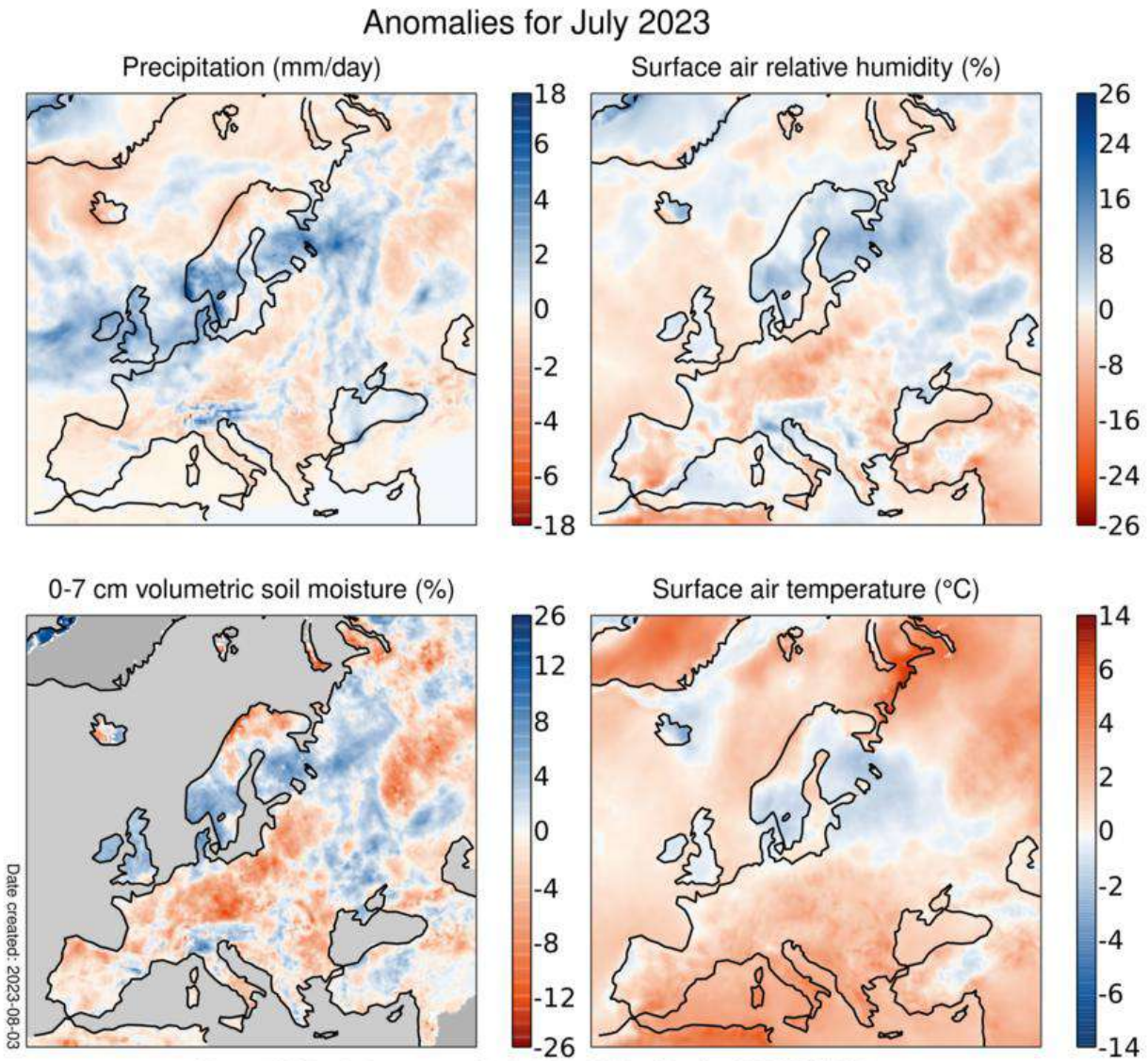
How different are their physiological mechanisms and what are the limits they impose?

The environment: the changing climate

Rainfall

SUPPLY

Soil water



Air humidity

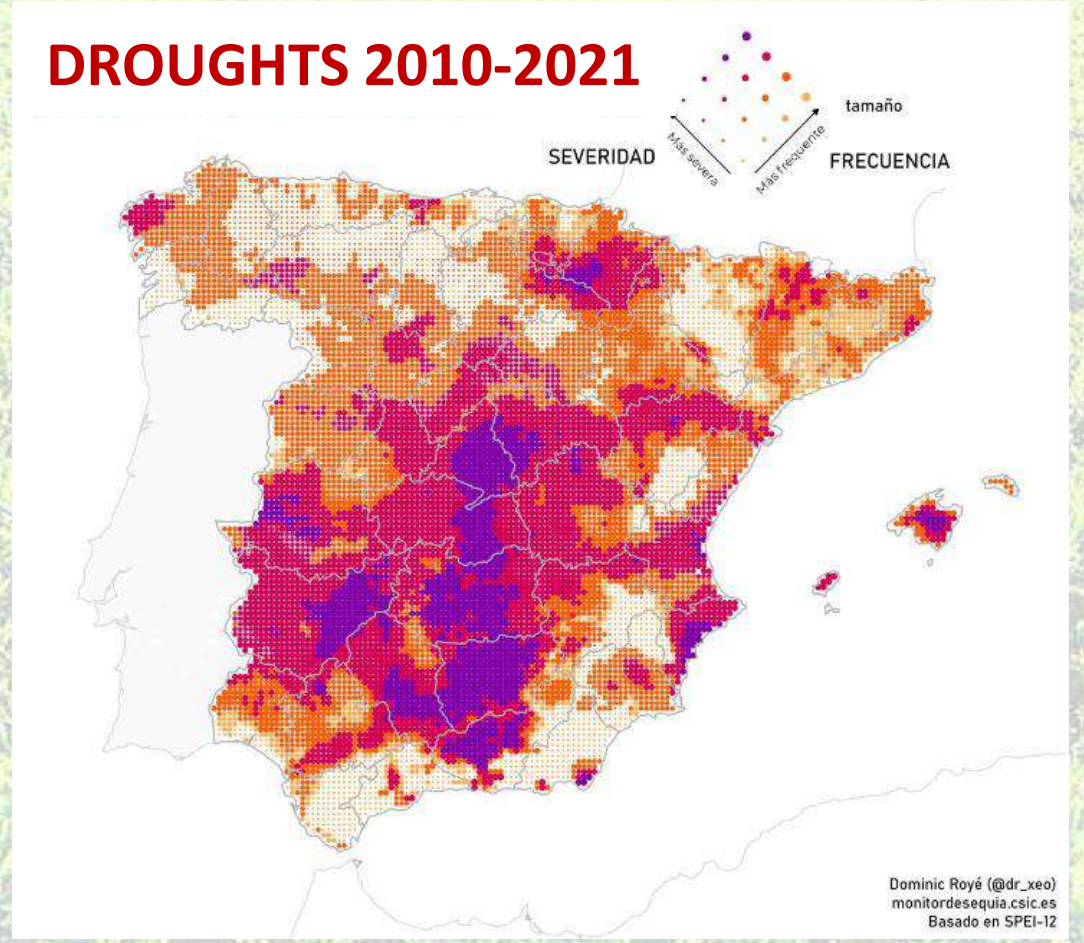
DEMAND

Air vapour pressure deficit (VPD)

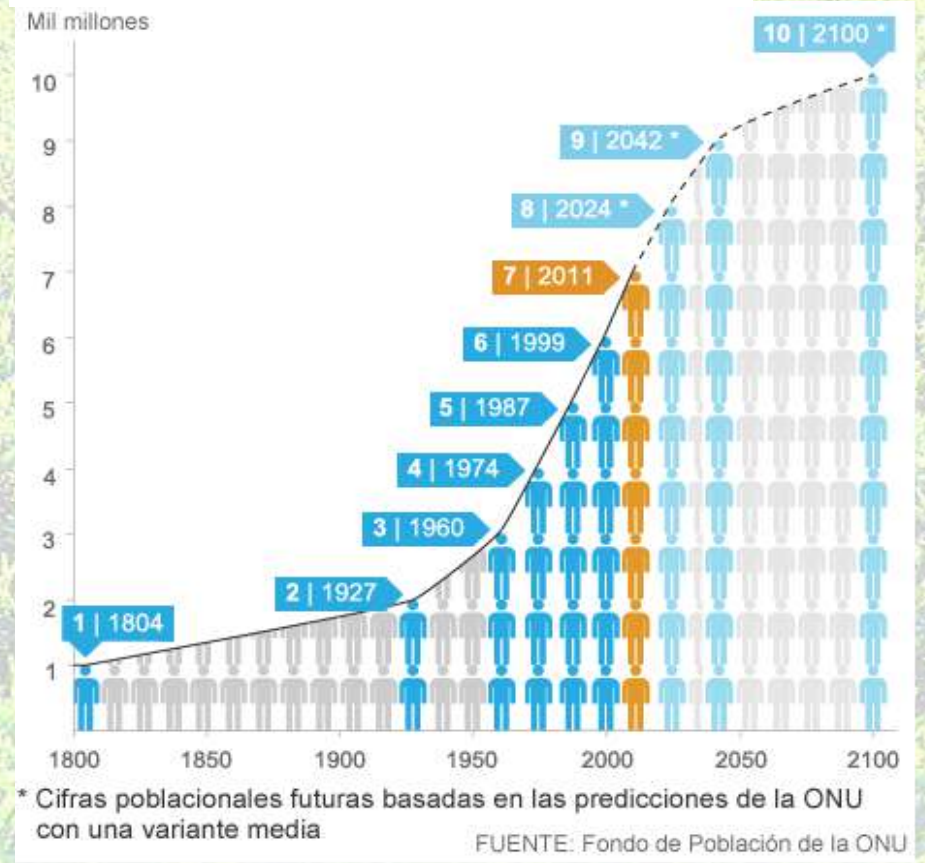
Temperature

The two challenges for crop breeders

DROUGHTS 2010-2021



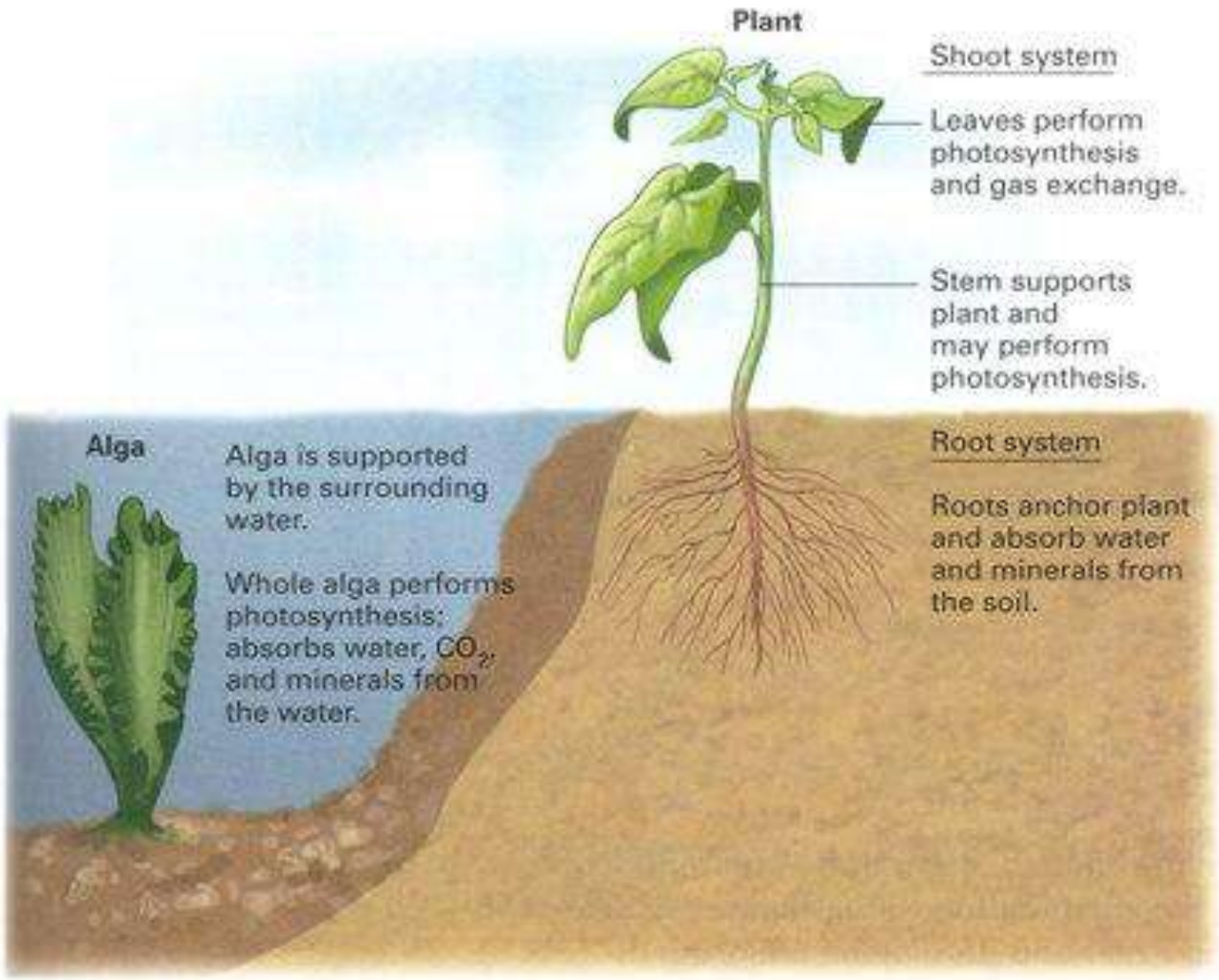
POPULATION DEMANDS



Higher Water Use Efficiency

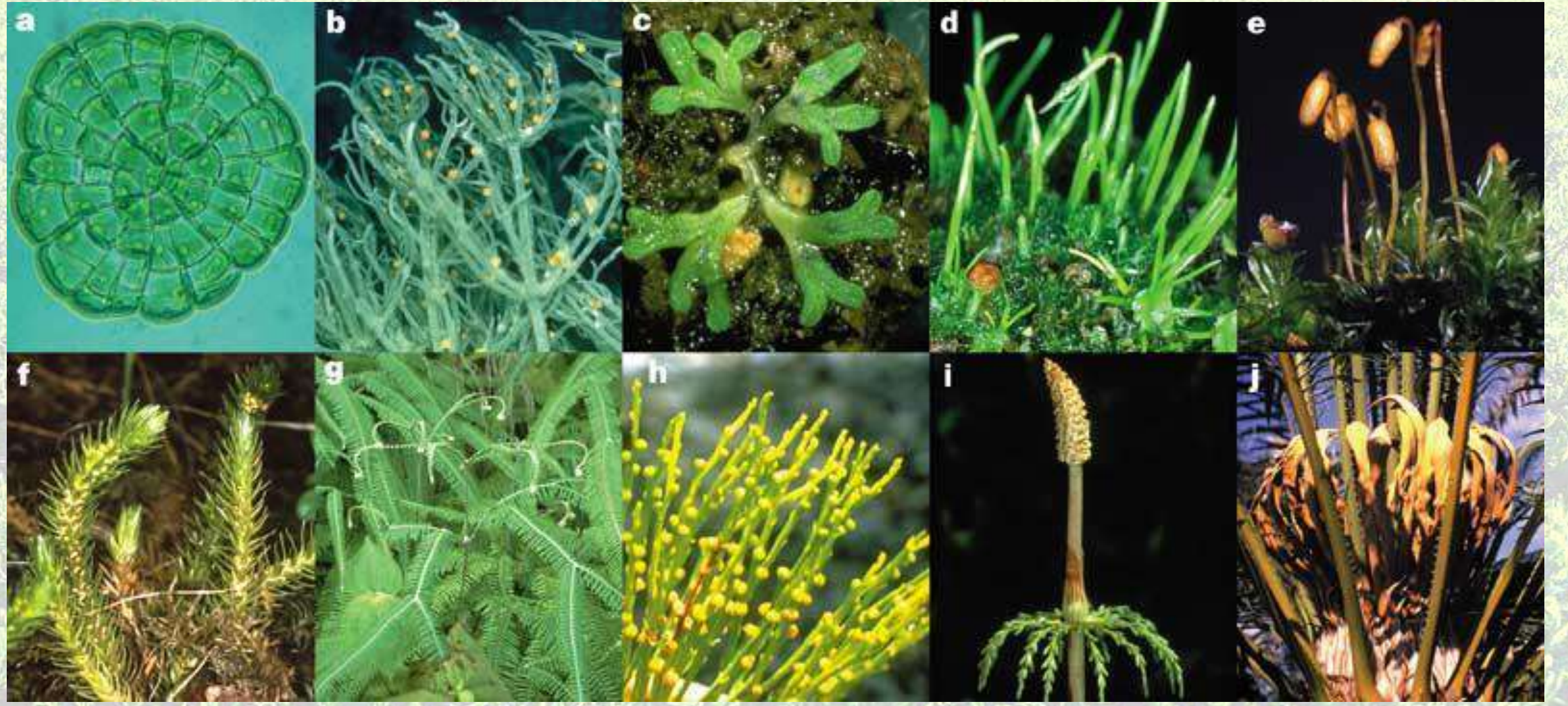
Higher Yield Capacity

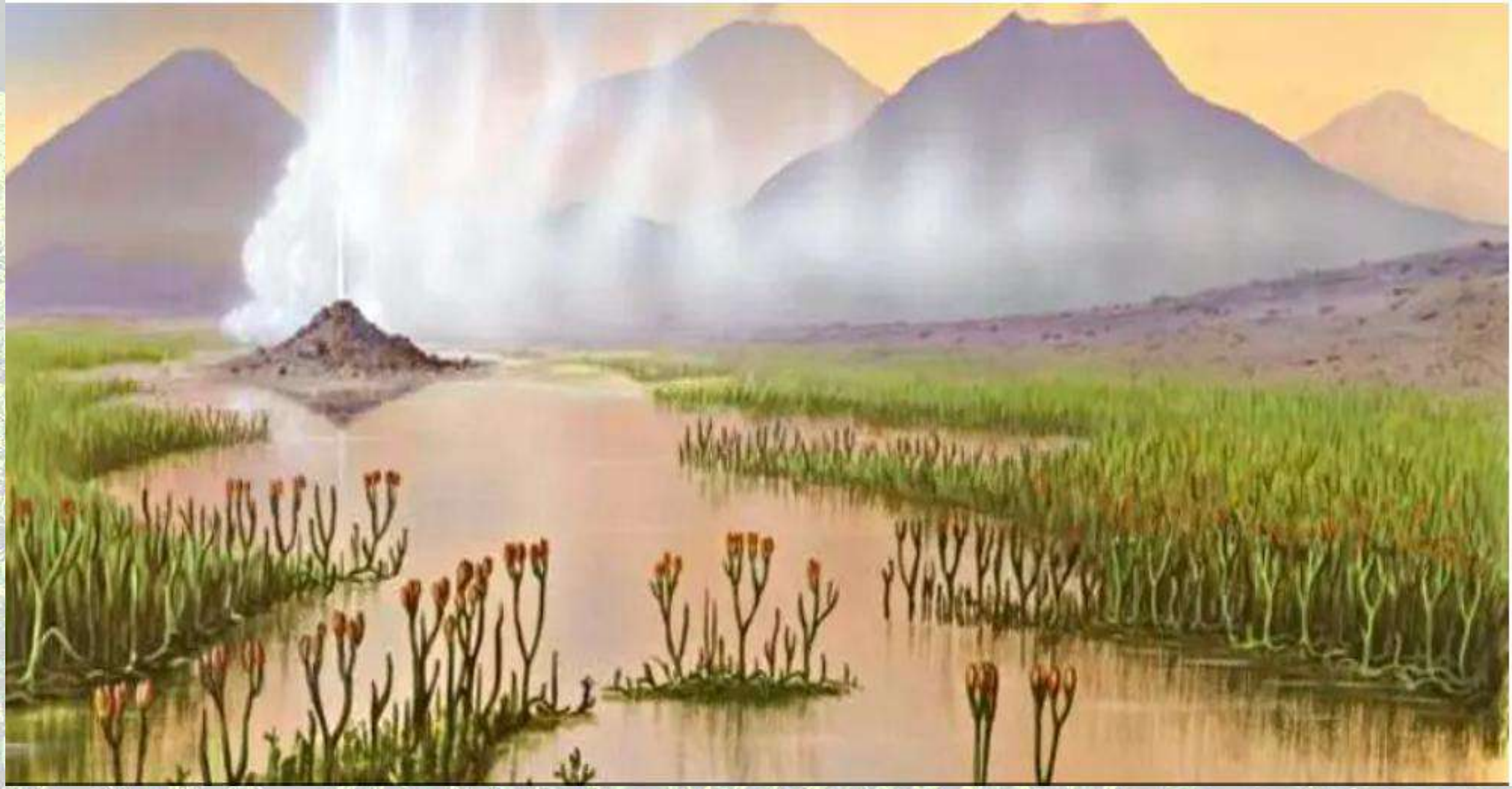
Challanges faced by plants to conquer earth



◀ **Figure 19-2** While algae live entirely in water, a plant lives in two environments: air and soil. A plant's organ systems are adapted to these two environments.

The conquer of earth

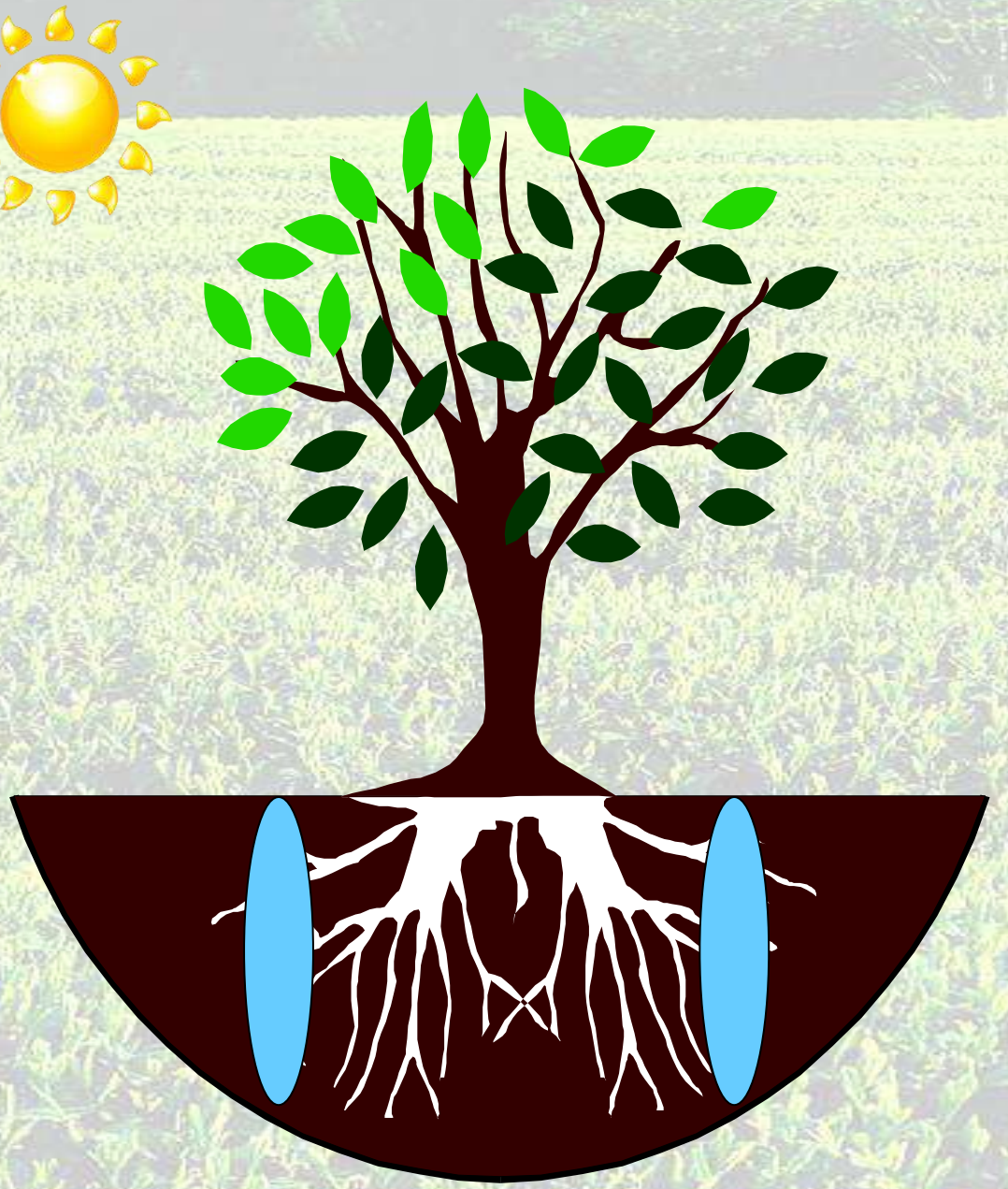




Silurian period (443-416 million years)


Cretaceus period (145-66 million years)





Demand

Supply

Atmosphere
Leaf area
Stomata
Crop load

Soil hydraulics
Plant hydraulics
Root area
Soil water

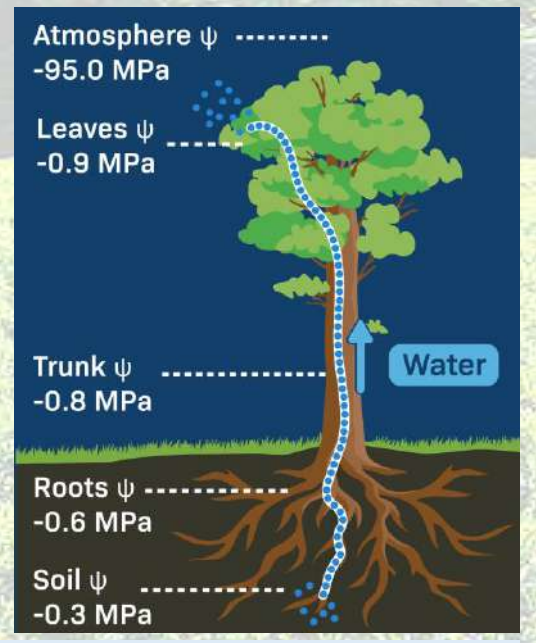
How does the plant keep the equilibrium?



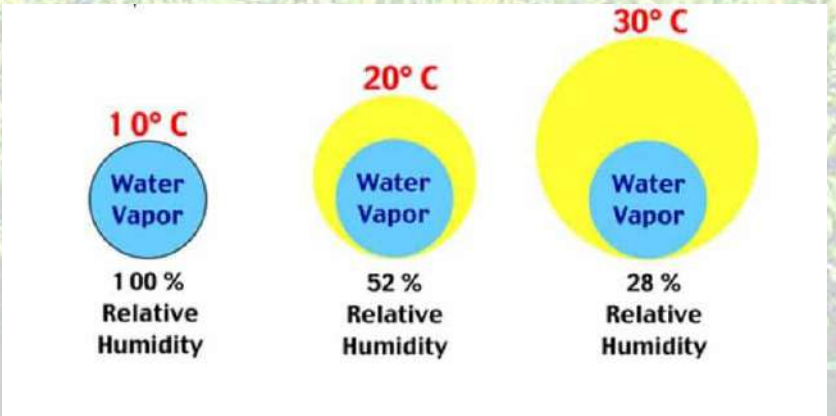


Demand = Supply

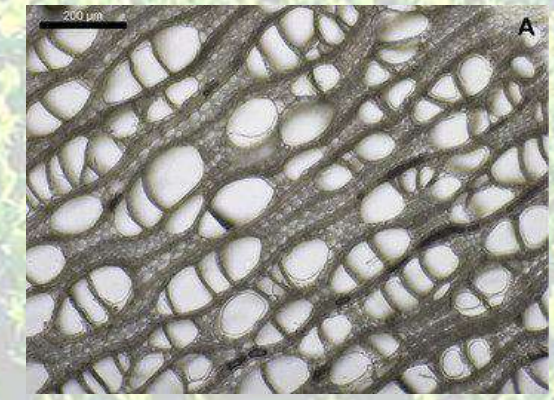
gs x VPD = $\Delta\Psi$ x K



Stomatal conductance x Atmospheric demand = **Water potential gradient x Hydraulic conductivity**







How does the plant keep the equilibrium? : VPD

Demand = Supply



Stomatal conductance

x

Atmospheric demand

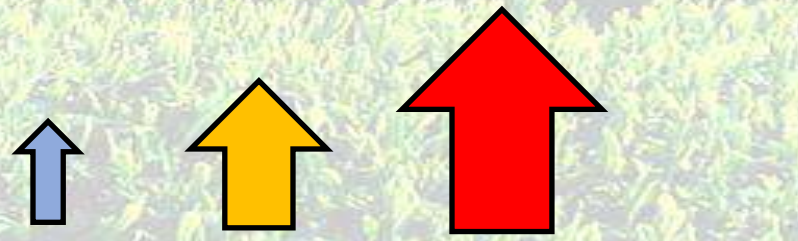
=



Water potential gradient

x

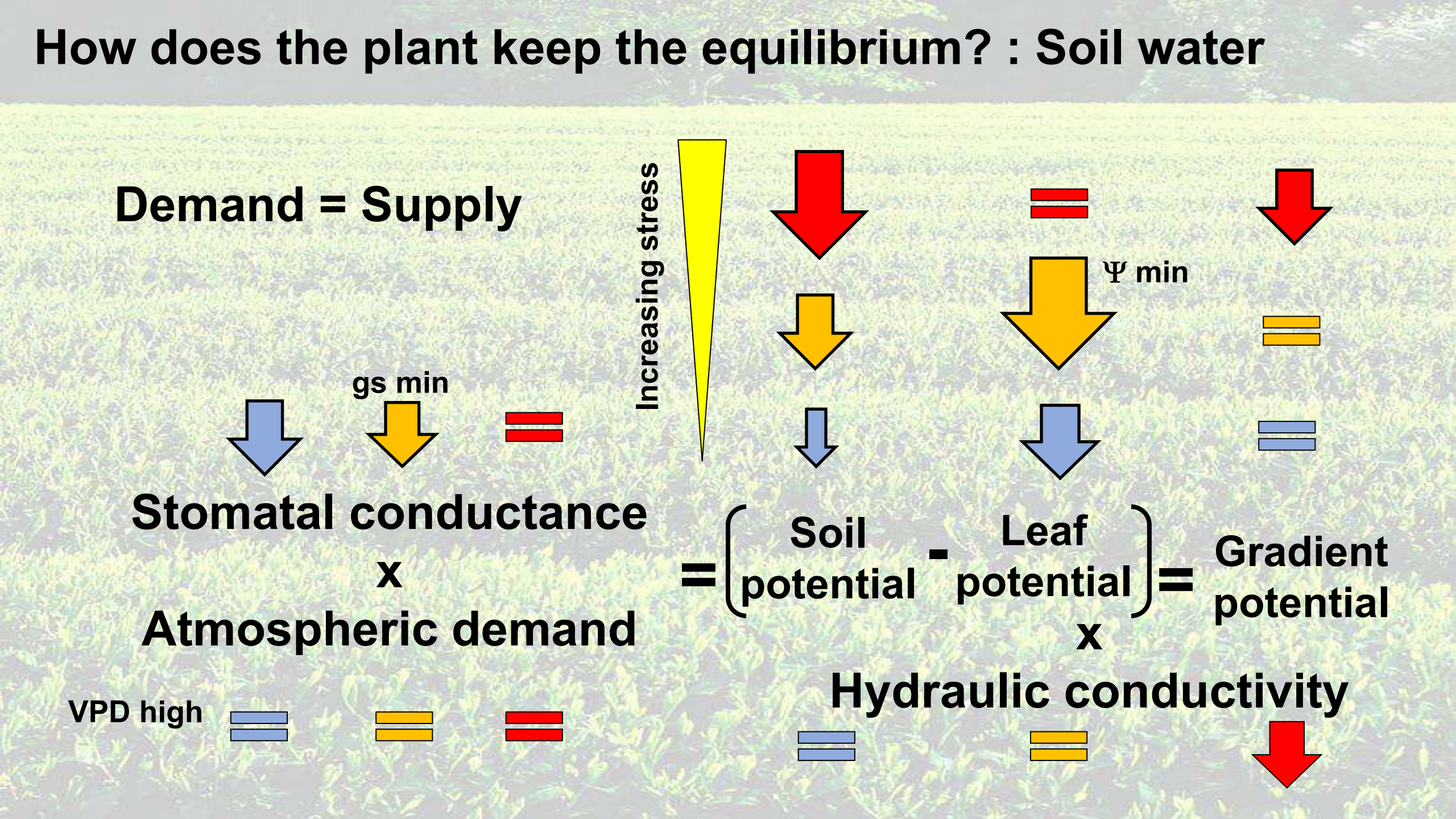
Hydraulic conductivity



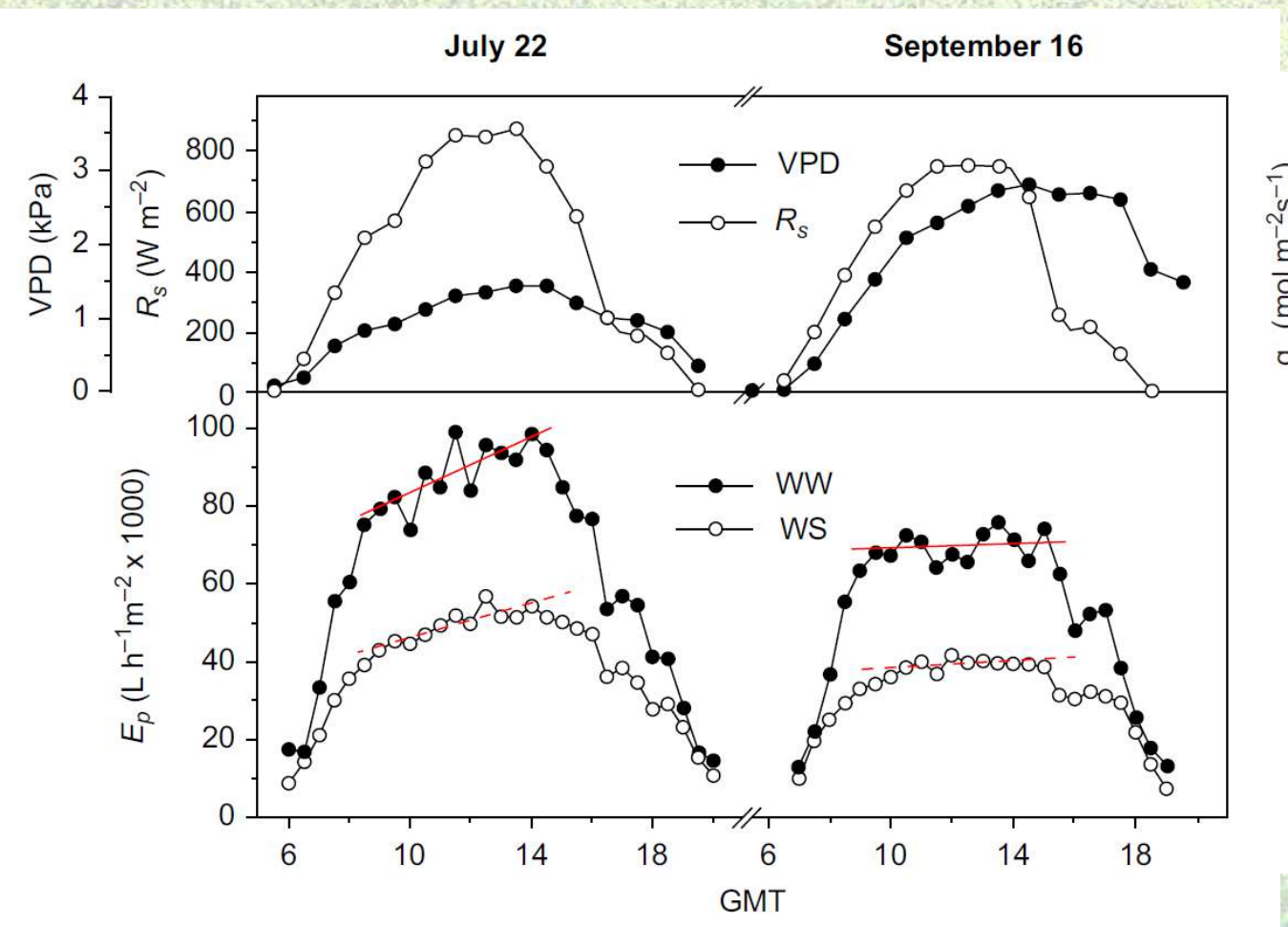


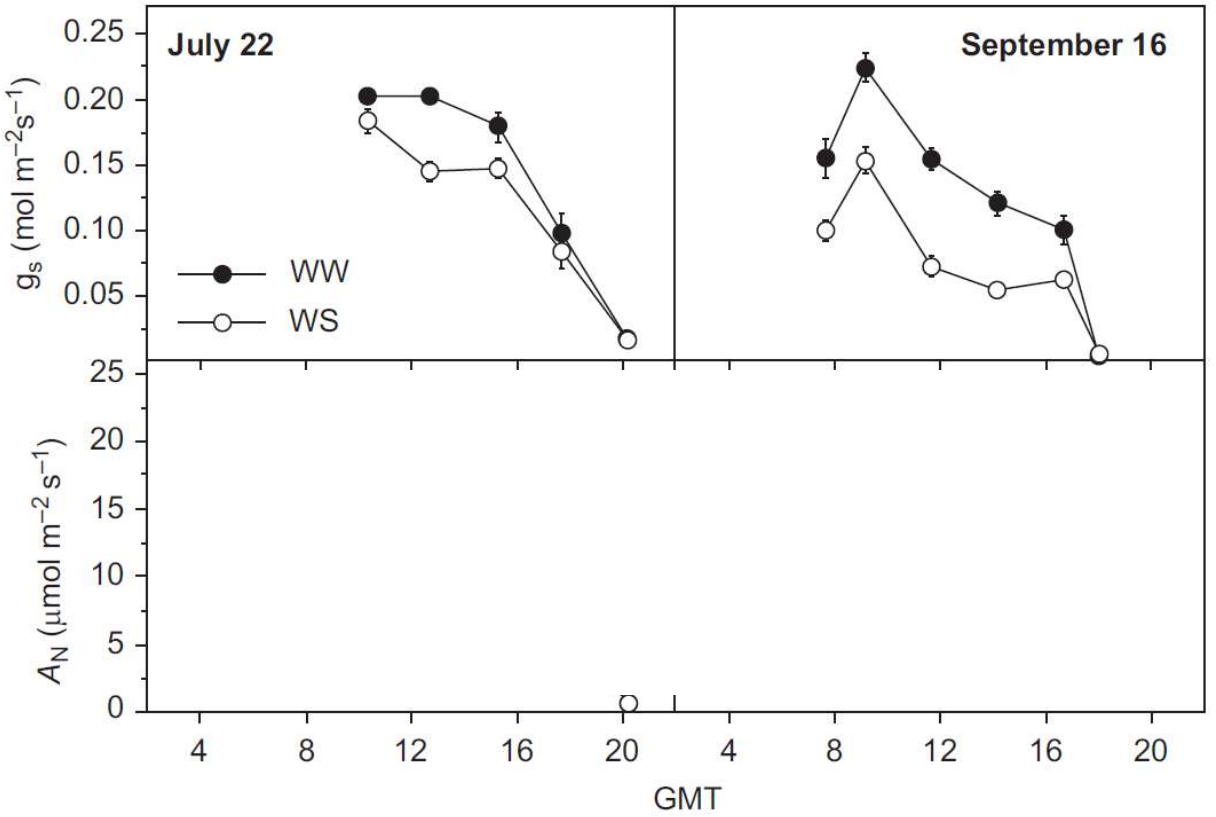
Increasing stress

How does the plant keep the equilibrium? : Soil water

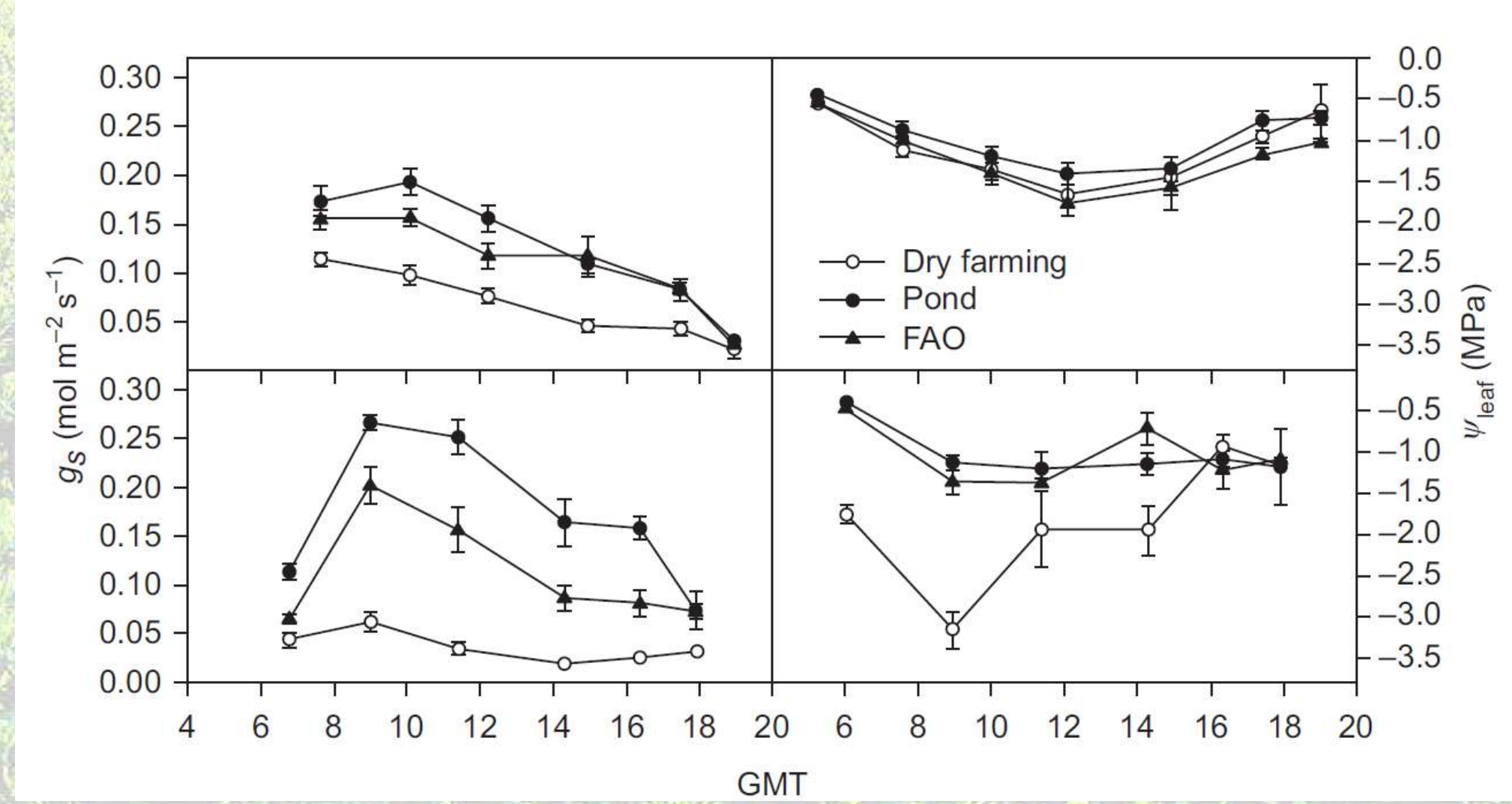


Real measured use of water by trees





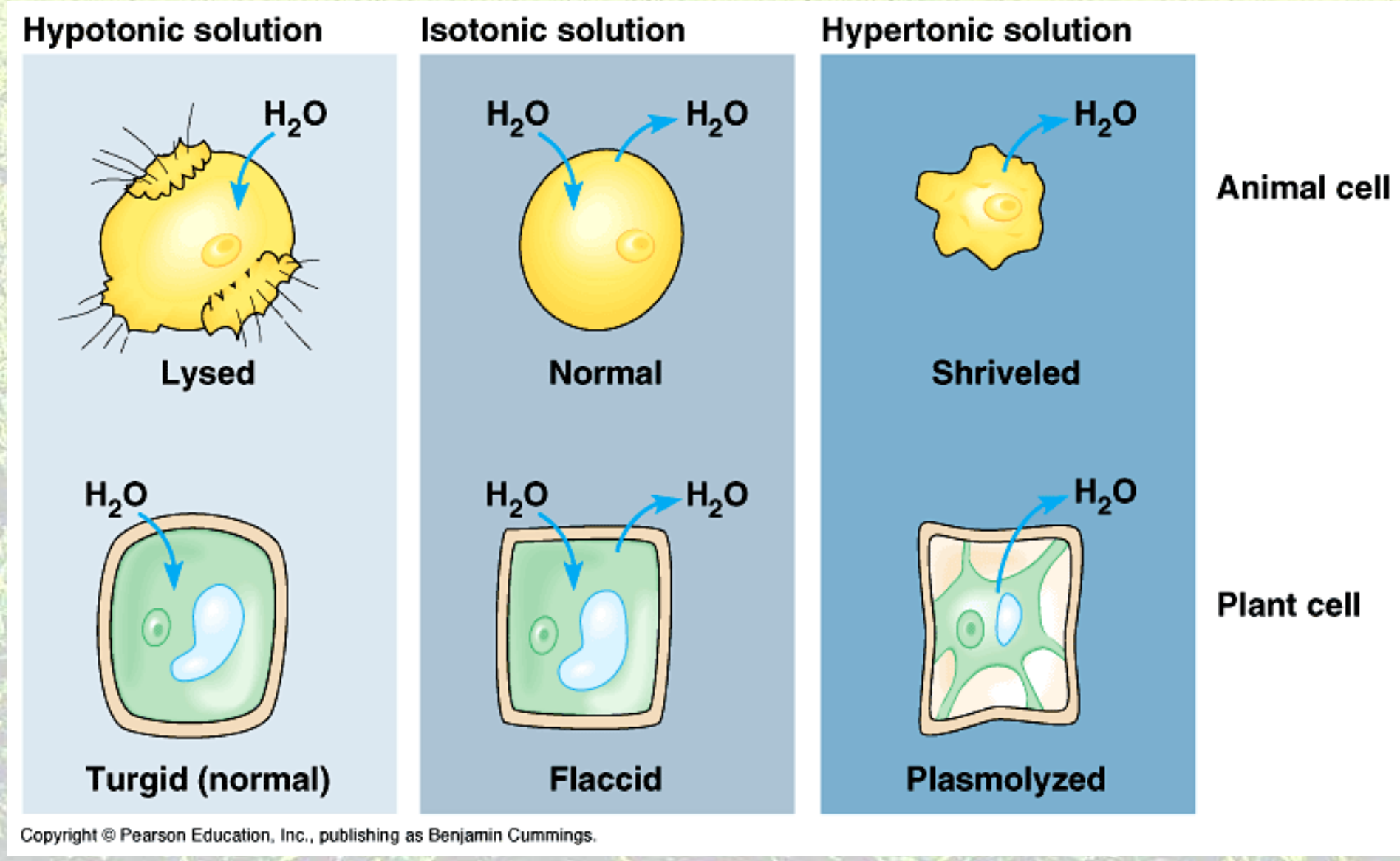
Real measured leaf water status and stomatal conductance



Main conclusions

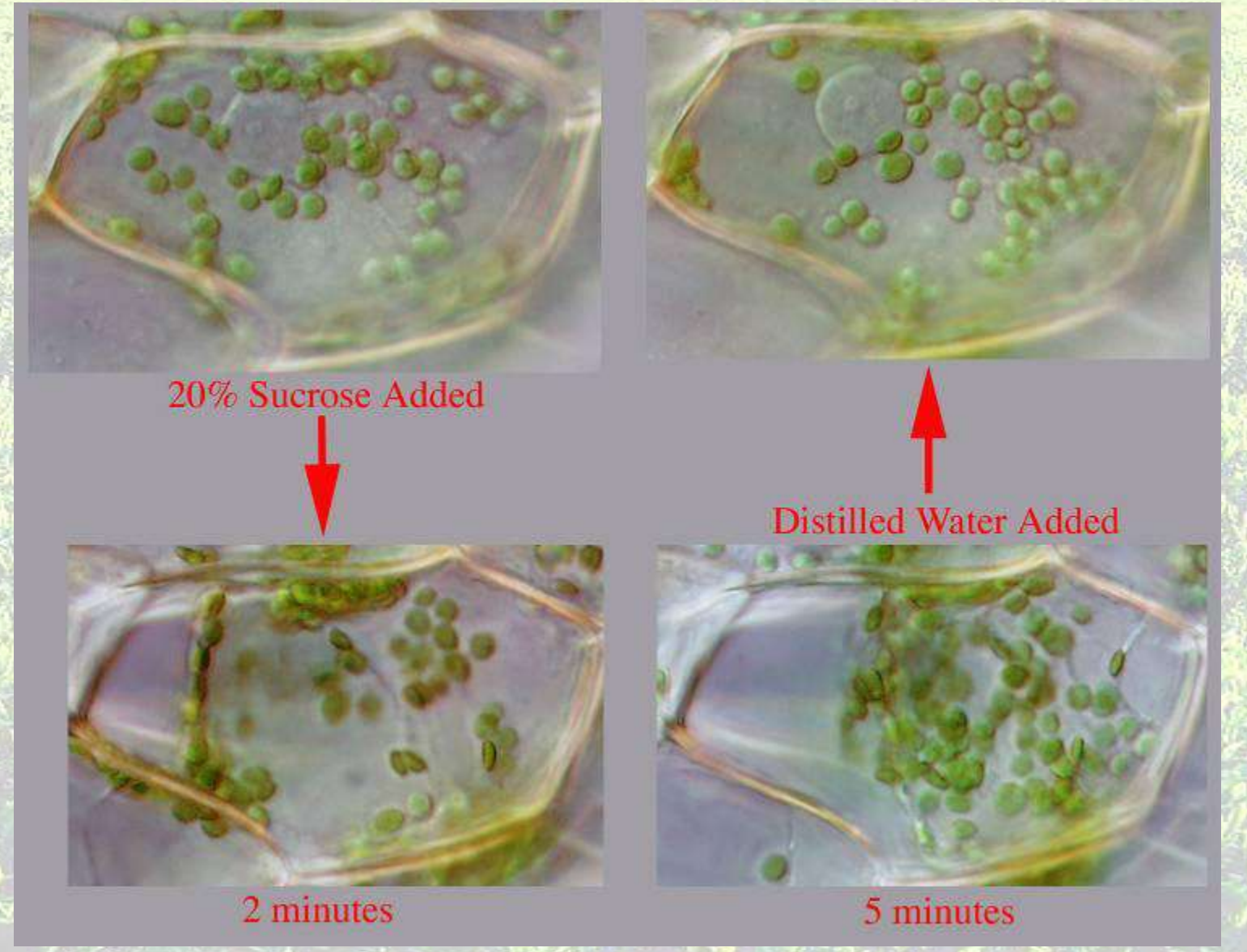
- ***Stomatal conductance regulation maintains the equilibrium***
- ***Plants have a minimum water potential as a limit***
- ***Hydraulic conductance is protected***
- ***Stomatal closure and overpassing minimum water potential must have a price.***

Water relations



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Relaciones hídricas



Onion cell

Water relations



Irrigation

+3 hours



The water potential is defined as Ψ_w :

$$\Psi_W = \Psi_P + \Psi_S + \Psi_G$$

where,

Ψ_P = pressure potential

Ψ_S = osmotic potential

Ψ_G = gravitatory potential

(only relevant in very high trees)

Water relations

$$\Psi_w = \Psi_P + \Psi_S$$

where,

Ψ_P = potencial de presión

it is positive

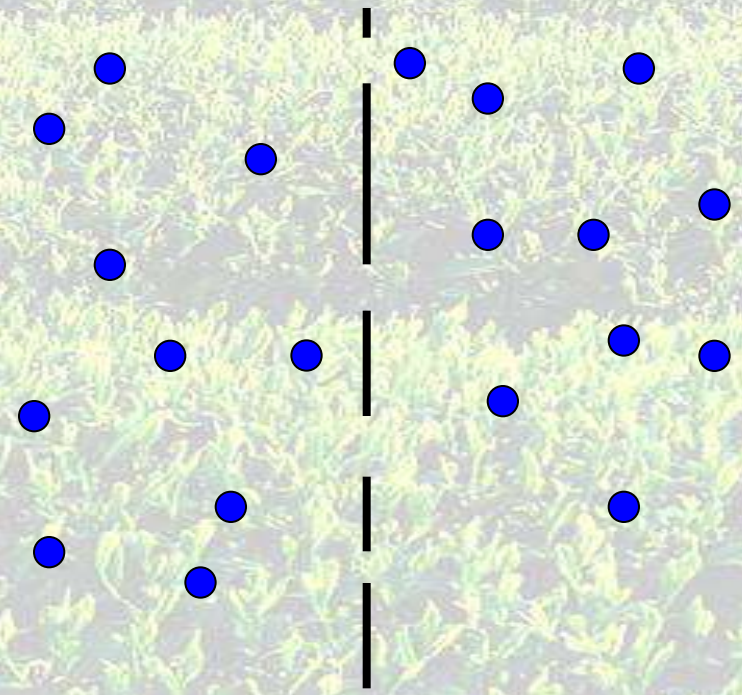
Ψ_S = potencial osmótico

it is negative and represents the effect of solutes; the addition of solutes always decreases the water potential

Water relations

Osmosis: Movimiento neto del agua a través de una membrana semipermeable.

Las moléculas de agua se pueden mover aleatoriamente gastando una mínima cantidad de energía cinética.



En este caso, agua destilada separada por una membrana semipermeable, existe un movimiento de moléculas de agua de un lado a otro de la membrana, pero no existe un movimiento osmótico neto.

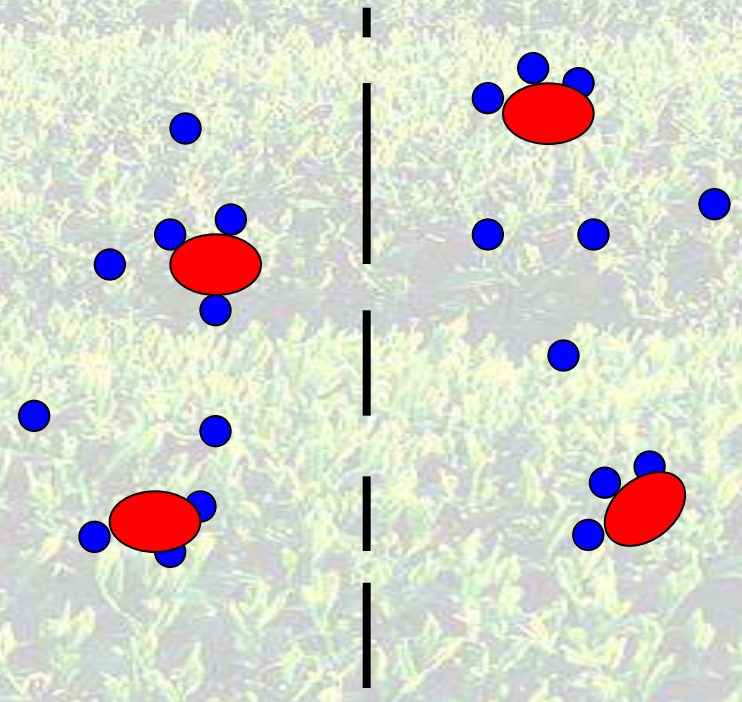
La cantidad de agua a un lado y otro de la membrana es siempre la misma. Se asume con el valor 0 al potencial osmótico del agua destilada.

$$\Psi_{S_{H_2O}} = 0$$

Water relations

Osmosis: Movimiento neto del agua a través de una membrana semipermeable.

Si hay alguna sustancia disuelta en el agua, la energía cinética de sus moléculas disminuye. Este descenso se debe a que el agua se agrega sobre la superficie de las nuevas moléculas en la mezcla.



En este caso, en una misma disolución separada por una membrana semipermeable, existe un movimiento de moléculas de agua de un lado a otro de la membrana, siendo este movimiento menor al del agua destilada.

Por eso asignamos valores negativos al potencial osmótico, ya que a mayor concentración de soluto menor es la energía que disponen las moléculas de agua para moverse.

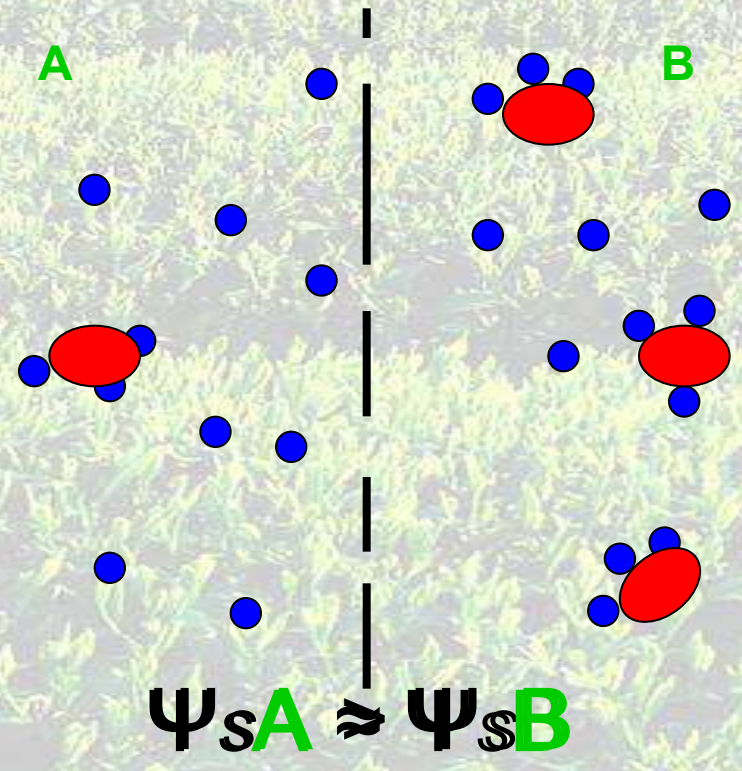
$\Psi_S = -RTC$

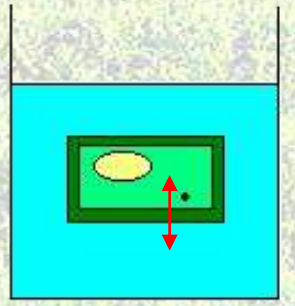
$\Psi_{SH_2O} = 0$

Water relations

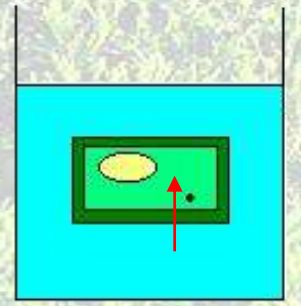
Osmosis: Movimiento neto del agua a través de una membrana semipermeable.

Separando con una membrana semipermeable dos soluciones con distinta concentración el agua se moverá desde la menos concentrada (Ψ_s mayor) a la más concentrada (Ψ_s menor).

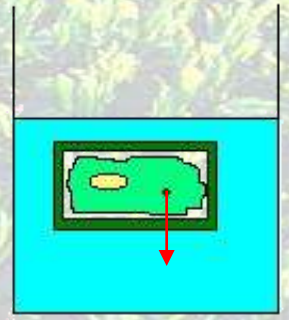




Solución Isotónica
Ψ_s Célula = -50
Ψ_s Medio = -50
No hay ósmosis neta.
No hay plasmolisis ni total turgencia.



Solución Hipotónica
Ψ_s Célula = -50
Ψ_s Medio = -20
Endosmosis.
Célula turgente.



Solución Hipertónica
Ψ_s Célula = -50
Ψ_s Medio = -80
Exosmosis.
Plasmolisis.

Water relations

¿How does the water potential change as a function of the cell water content?

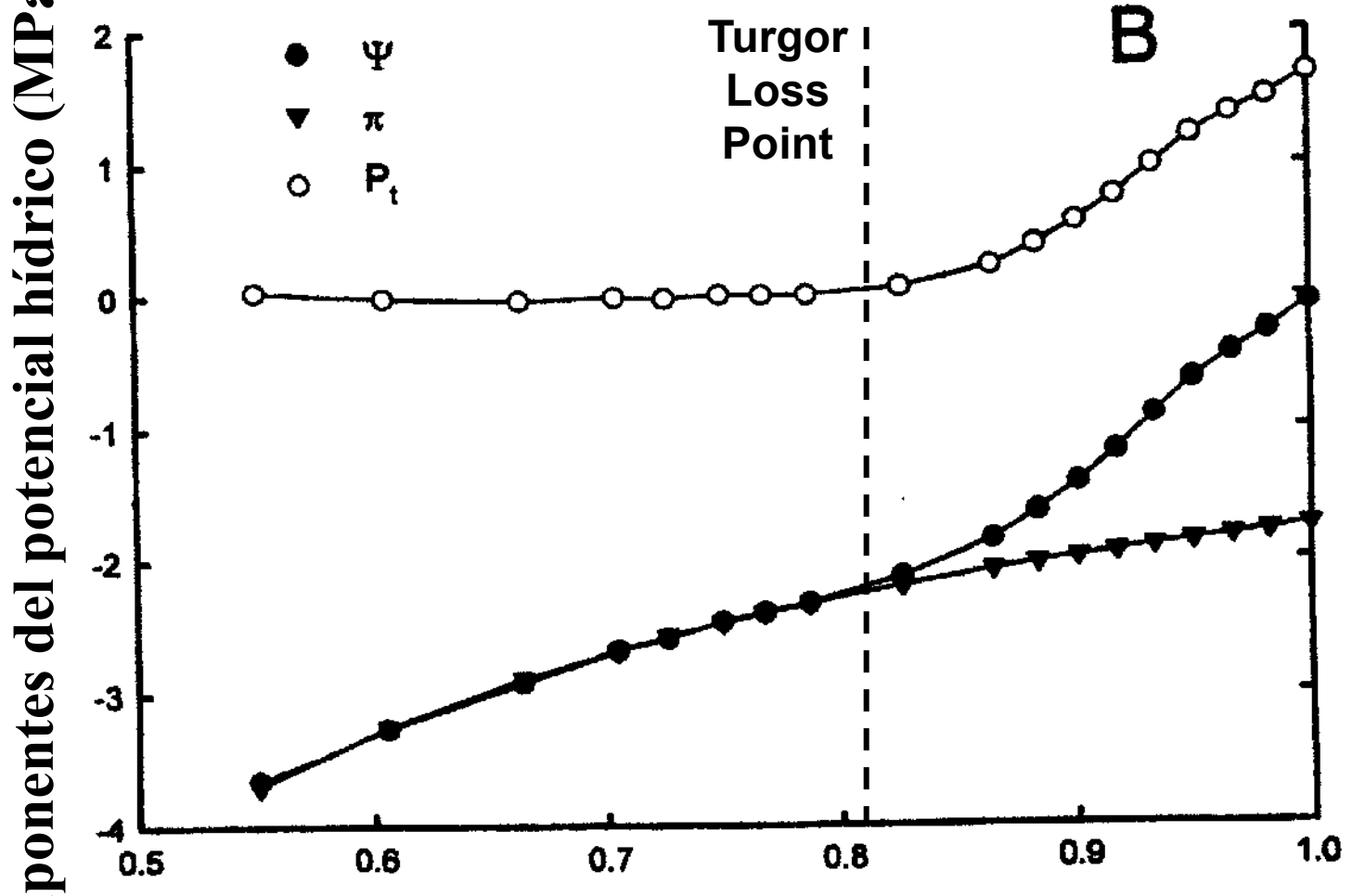
$$d\Psi_w = d\Psi_s + d\Psi_p$$

$$d\Psi_s = -\Psi_s \frac{dV}{V} \qquad d\Psi_p = \varepsilon \frac{dV}{V}$$

Bulk elasticity modulus

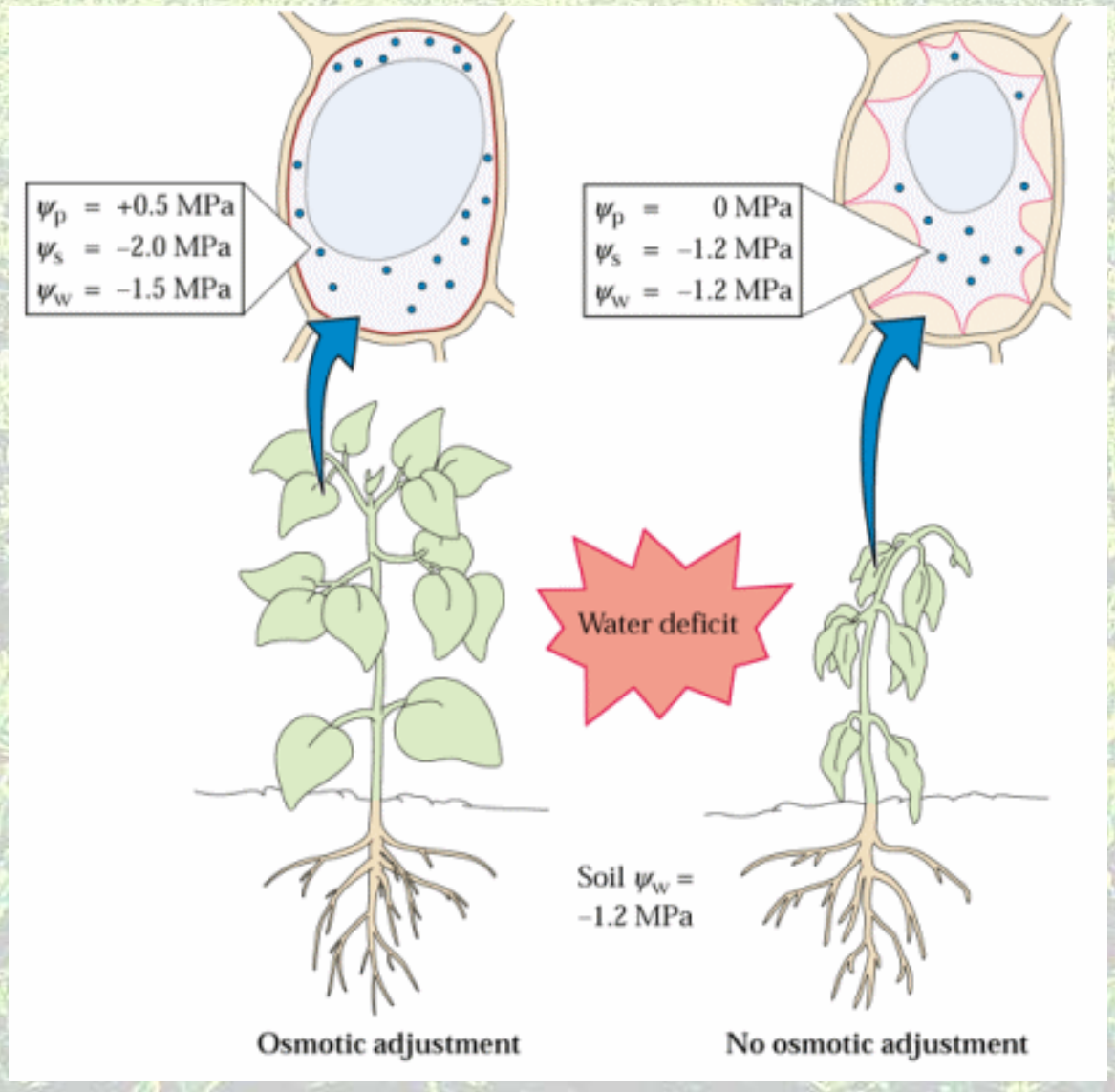
Most of the change in water potential is driven by the elastic modulus!!

Diagrama de Höfler - Thoday

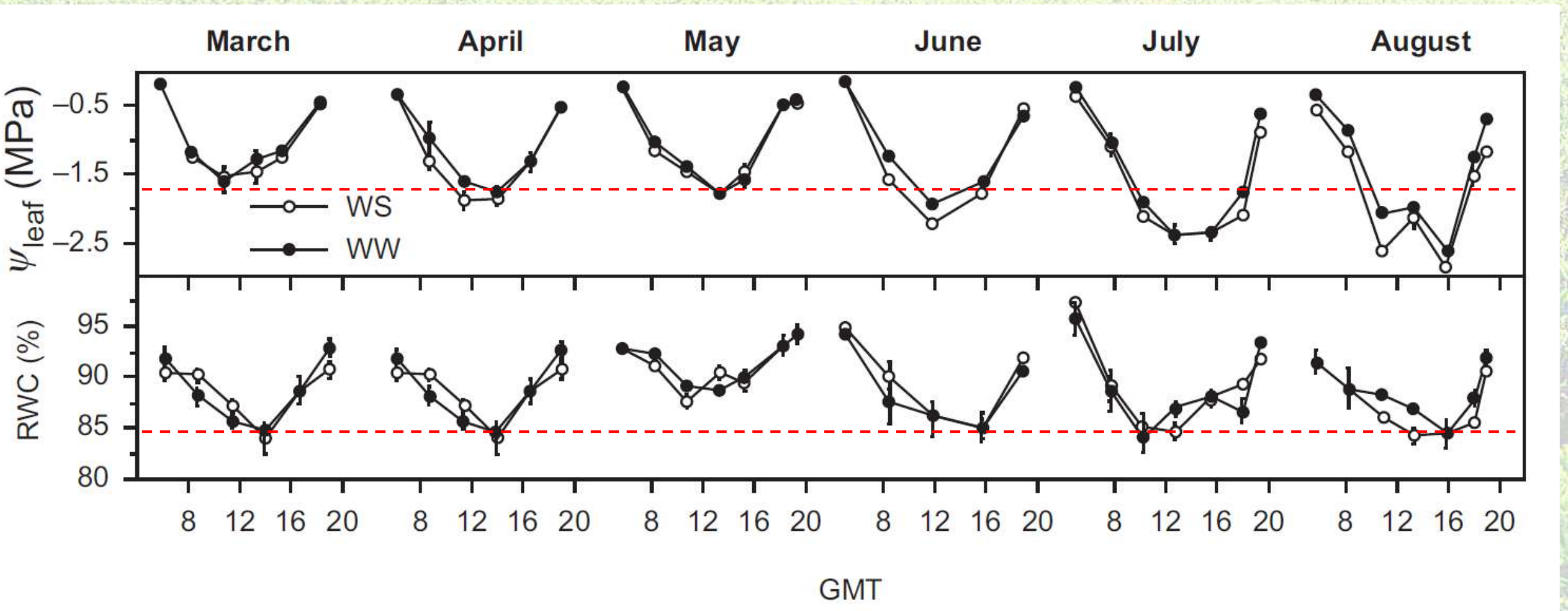


Fuente: Tyree (1999)

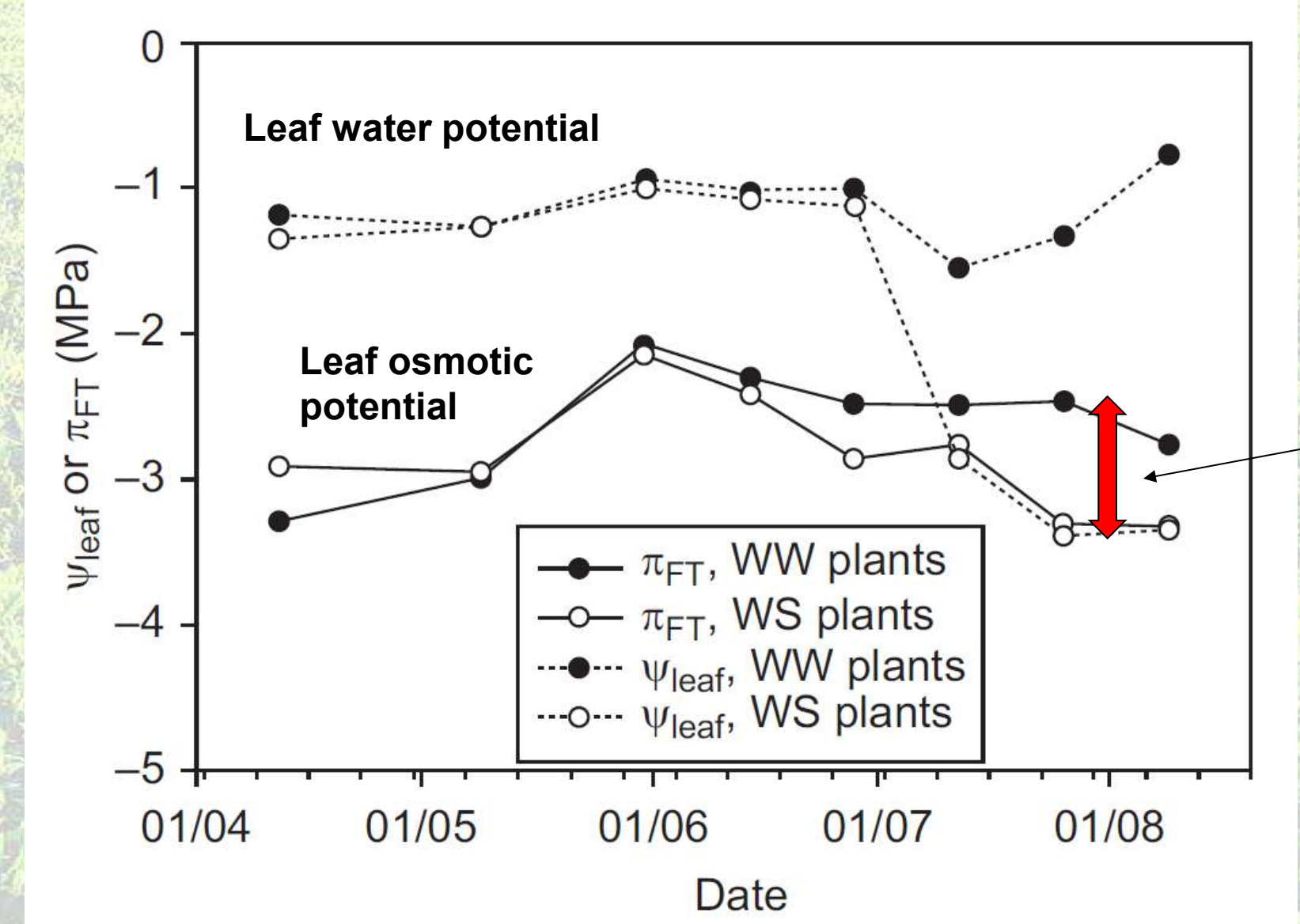
Osmotic adjustment



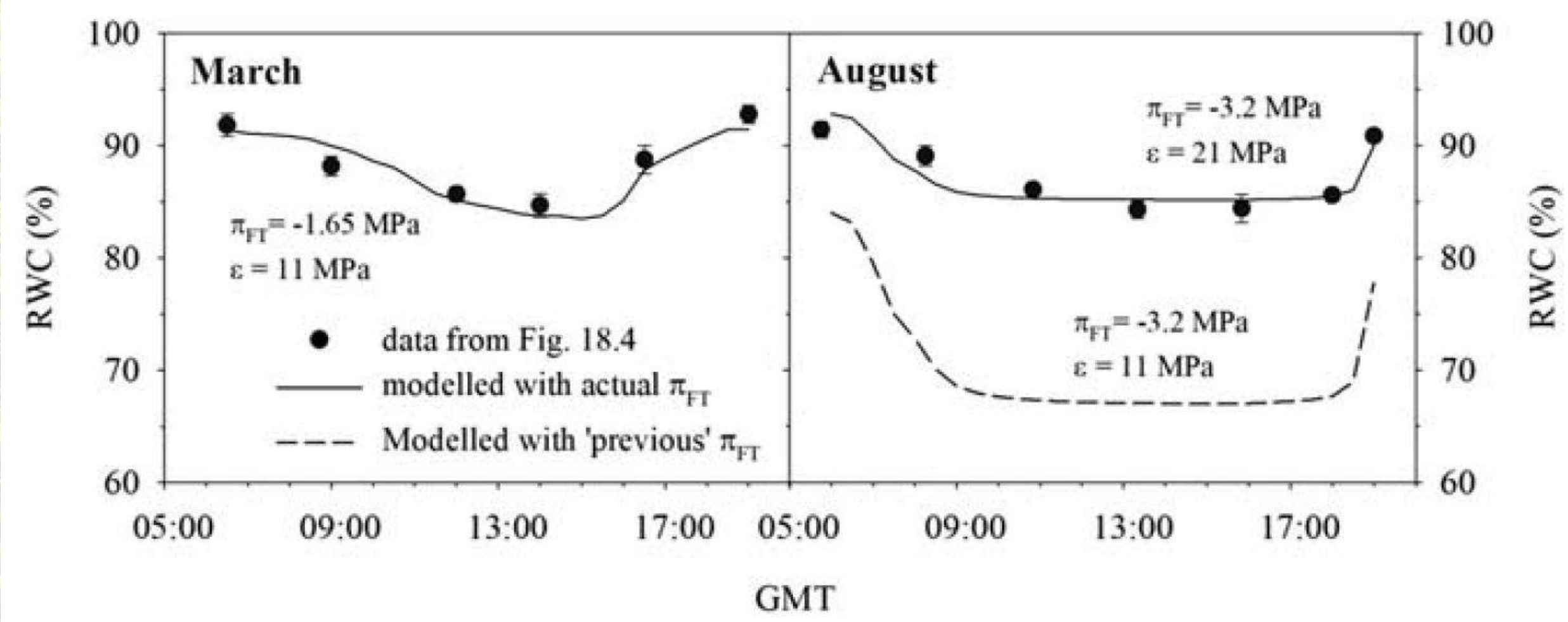
Water relations: the example of olive trees



Water relations: the example of olive trees



Water relations: the example of olive trees



Question:

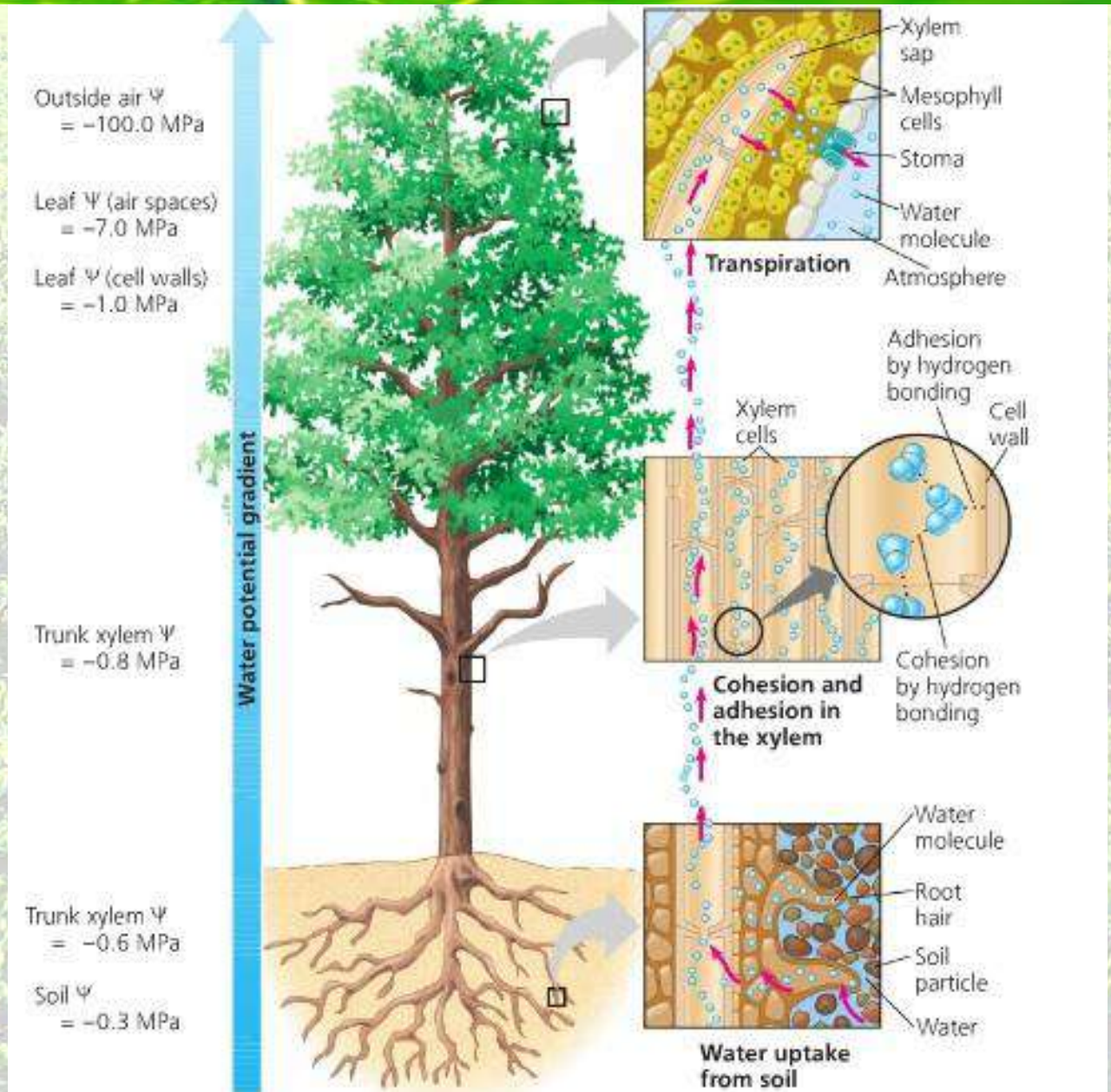
But if the plants can do osmotic adjustment and decrease it water potential as much as they want to uptake water from drying soils …

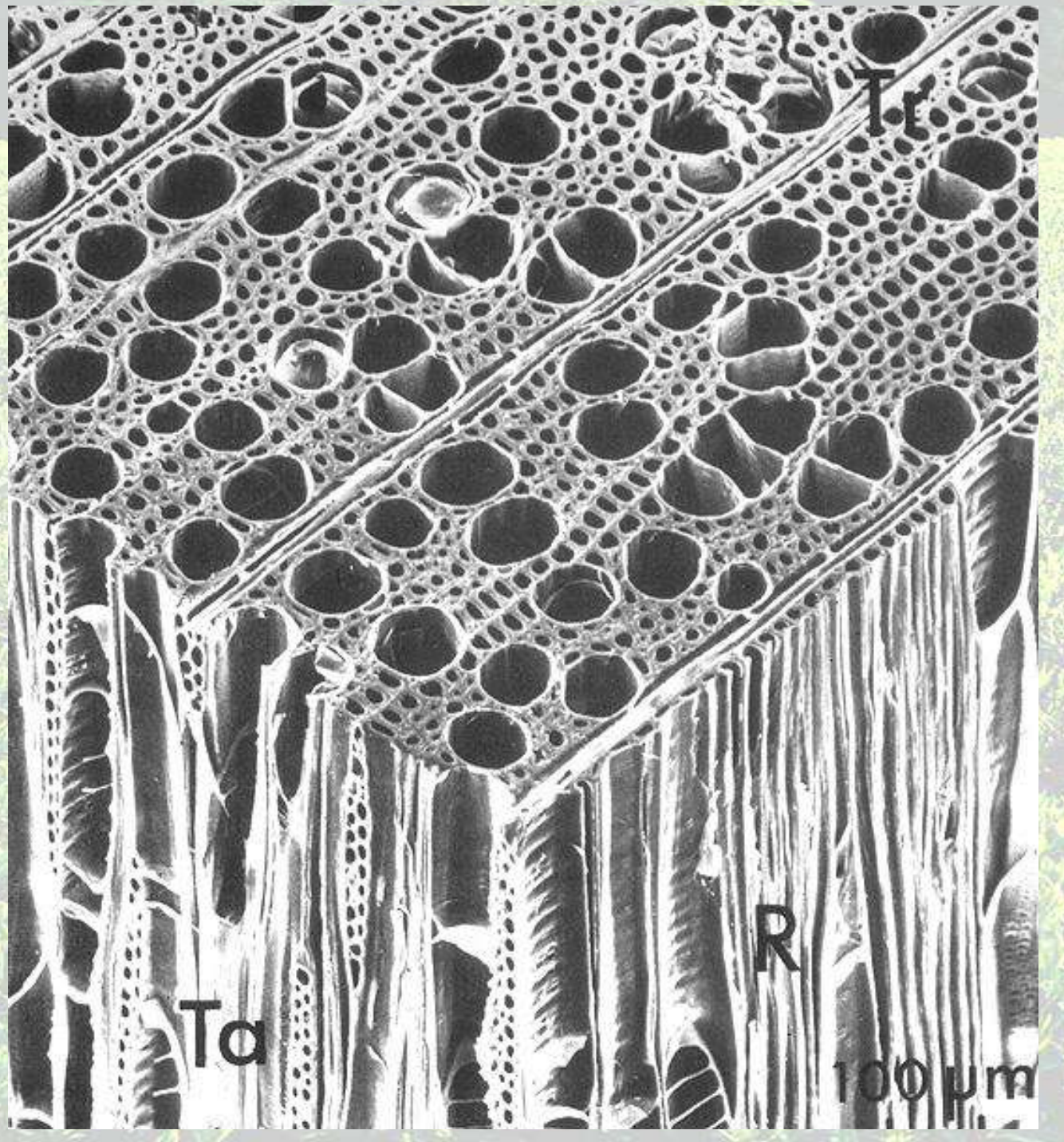


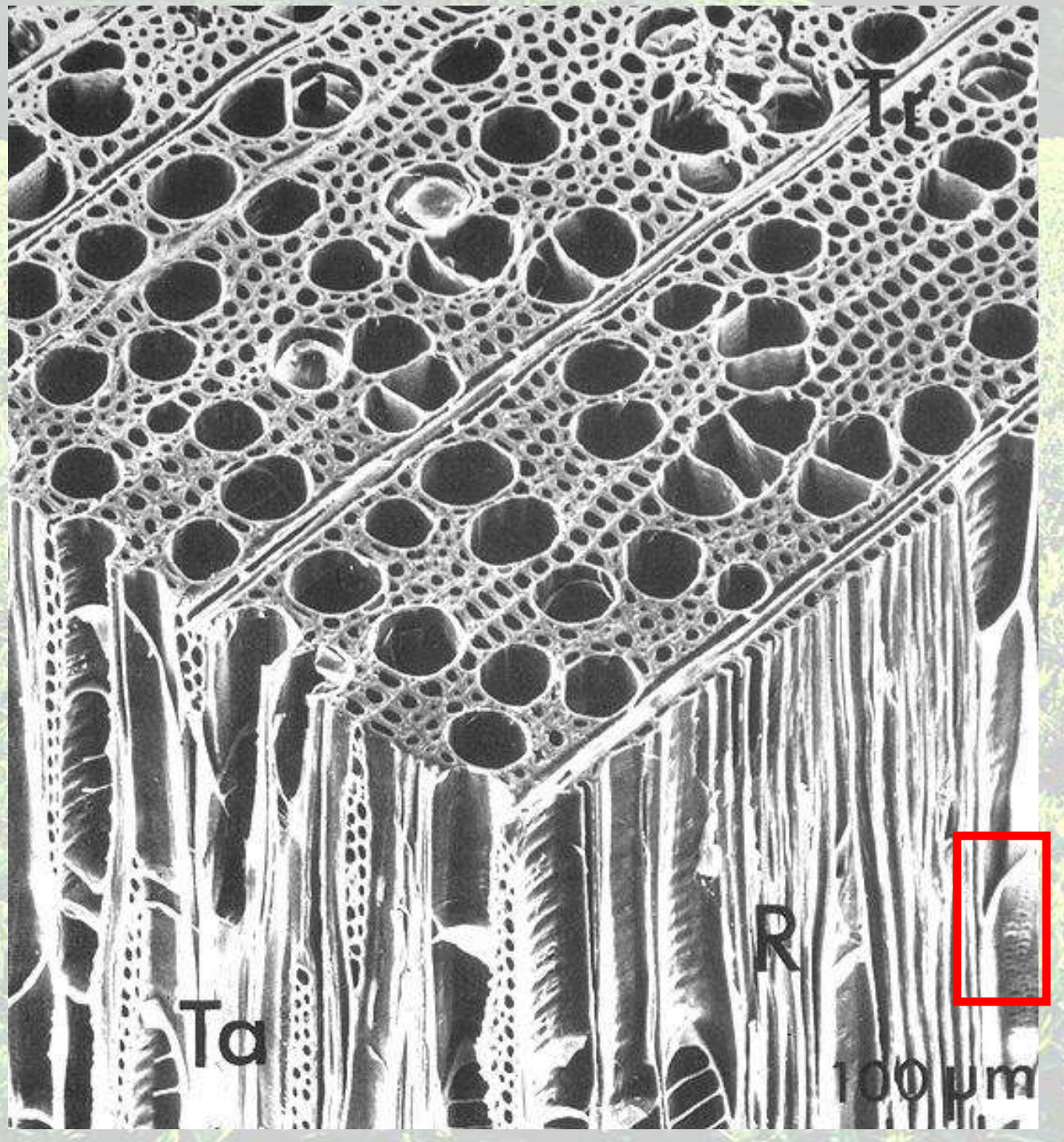


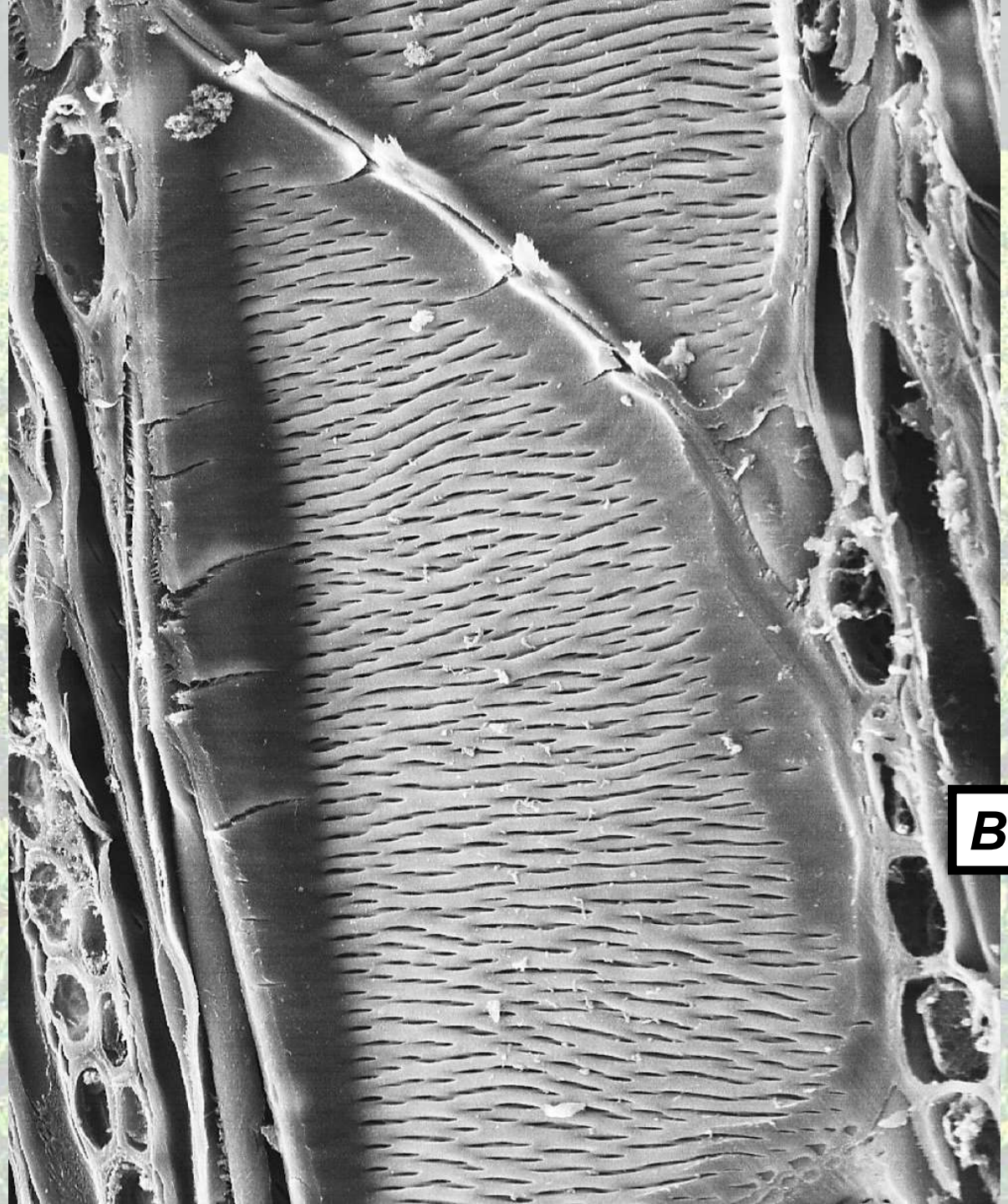
… why do they not do endlessly and maintain their stomata open to keep high photosynthesis?

Water transport



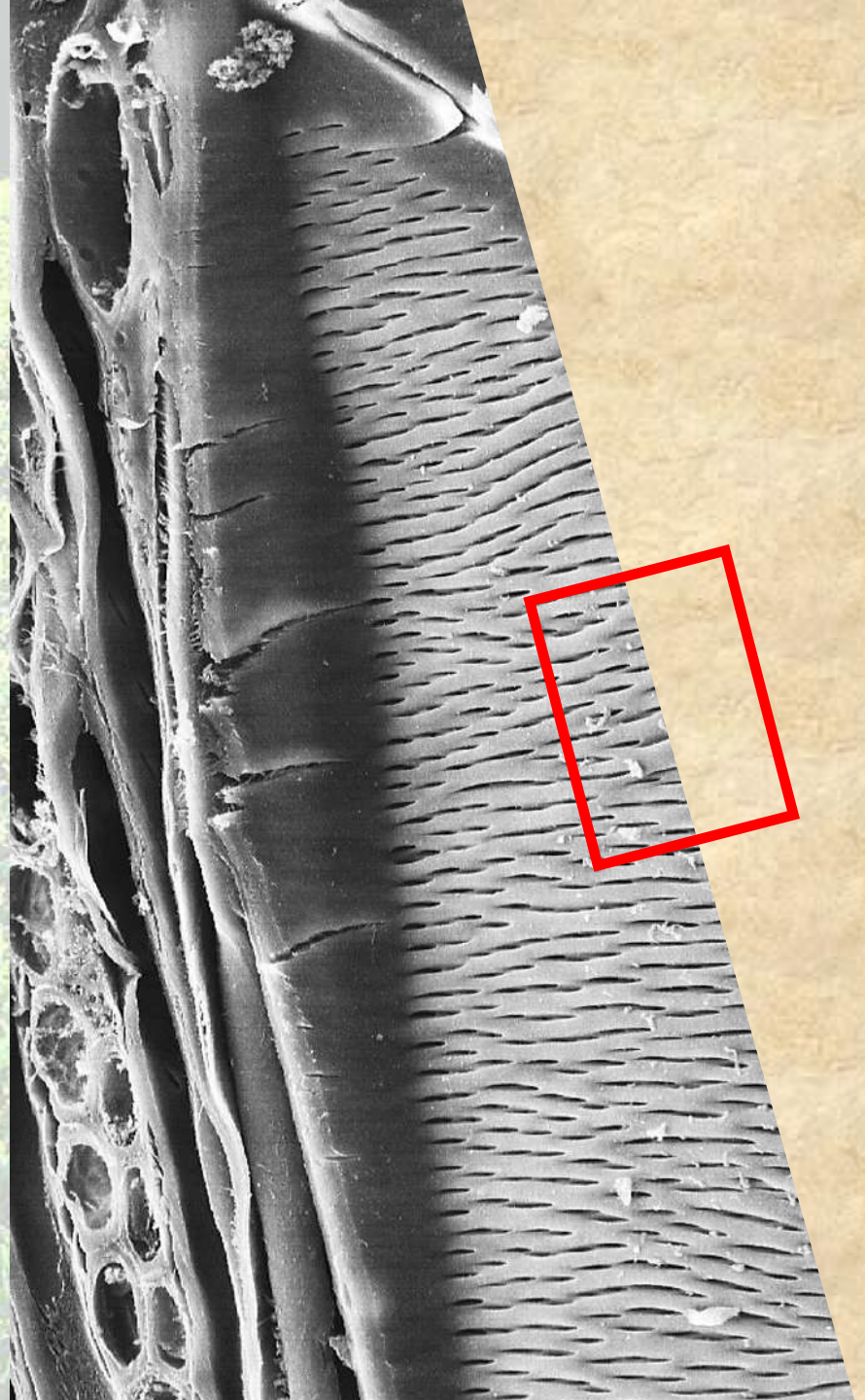

Tr
Ta
R
100 µm


Tr
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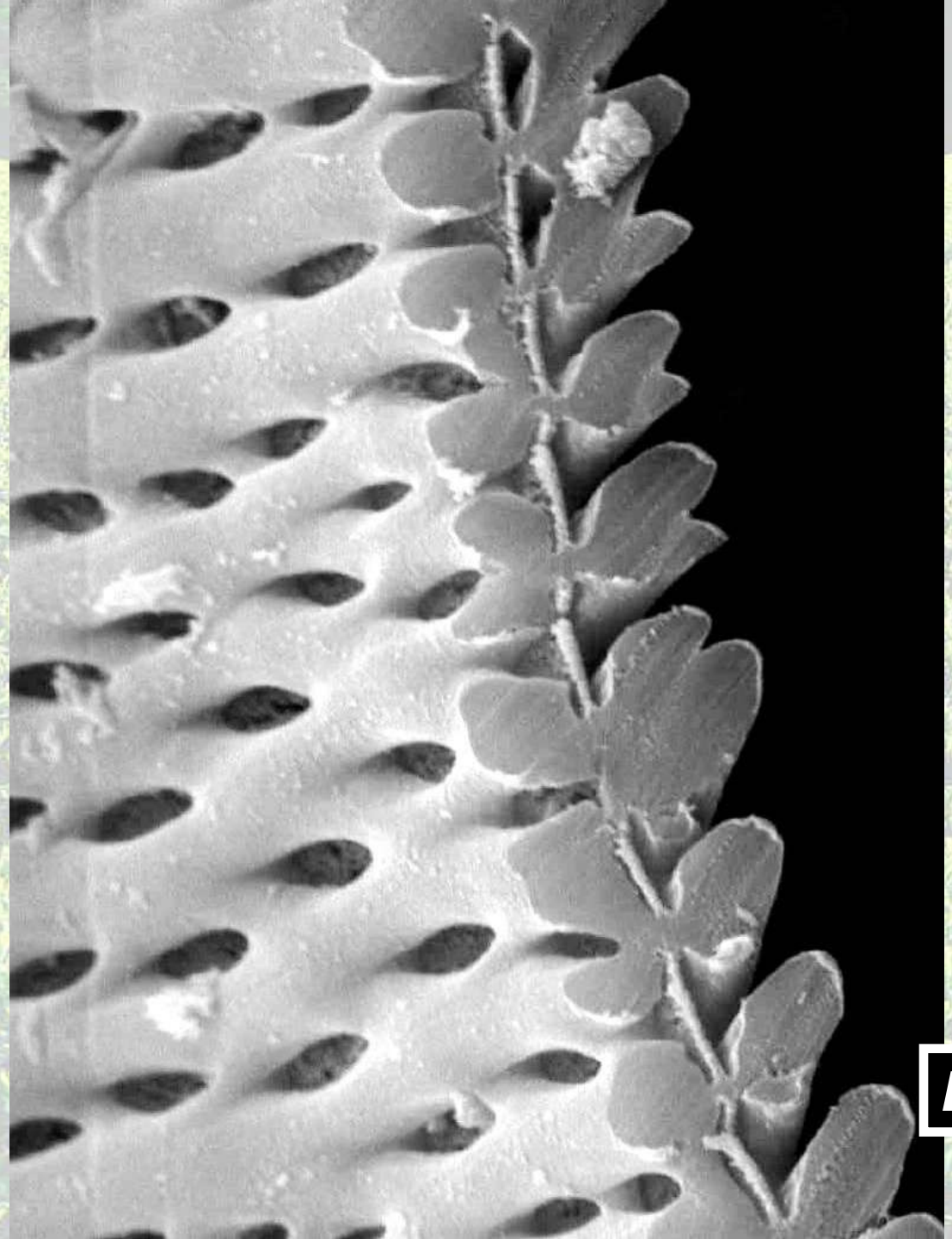


Betula nigra

Photo:
Jarmila Pittermann



Betula nigra



Betula nigra

Photo: Jarmila Pittermann

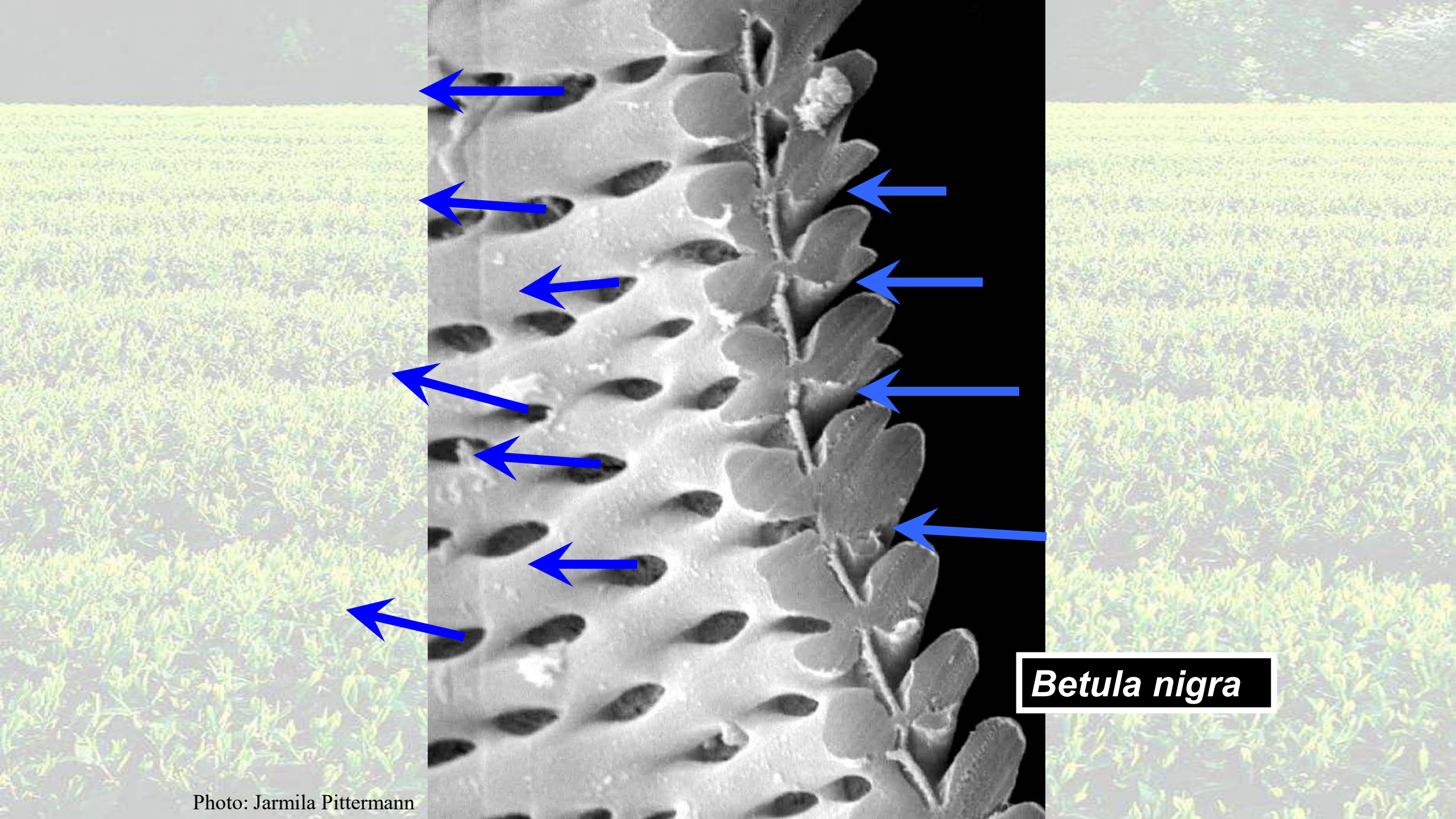
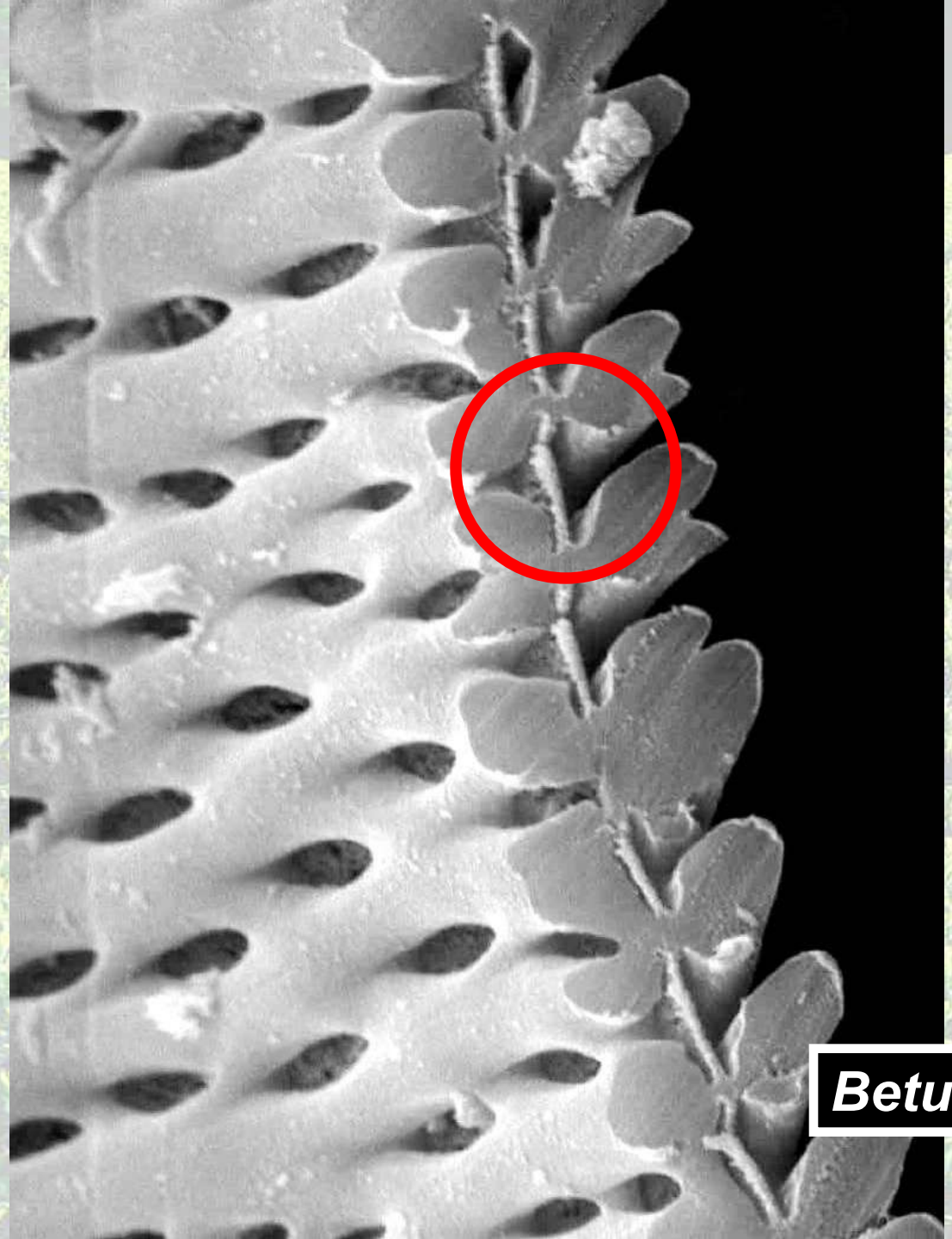
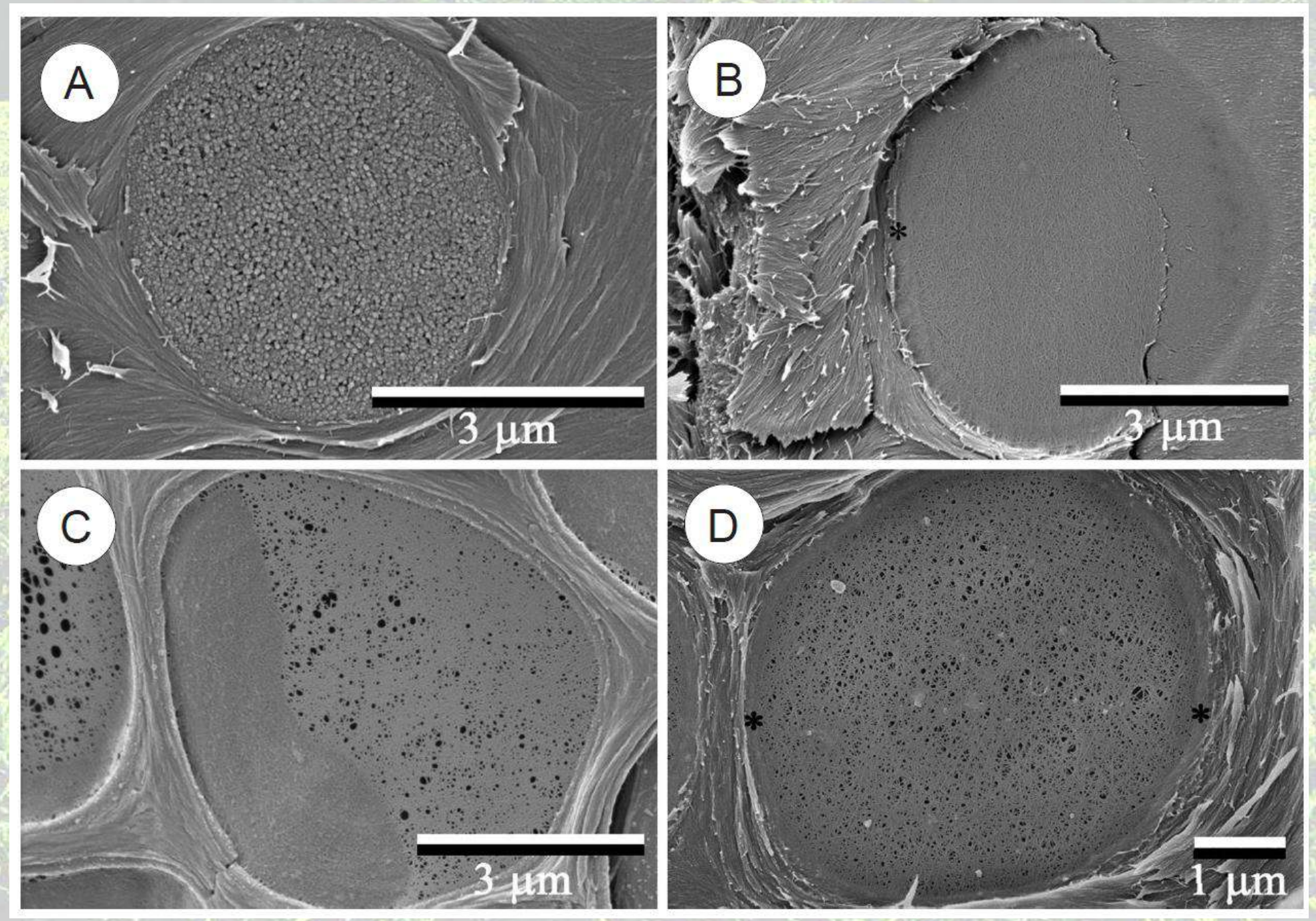


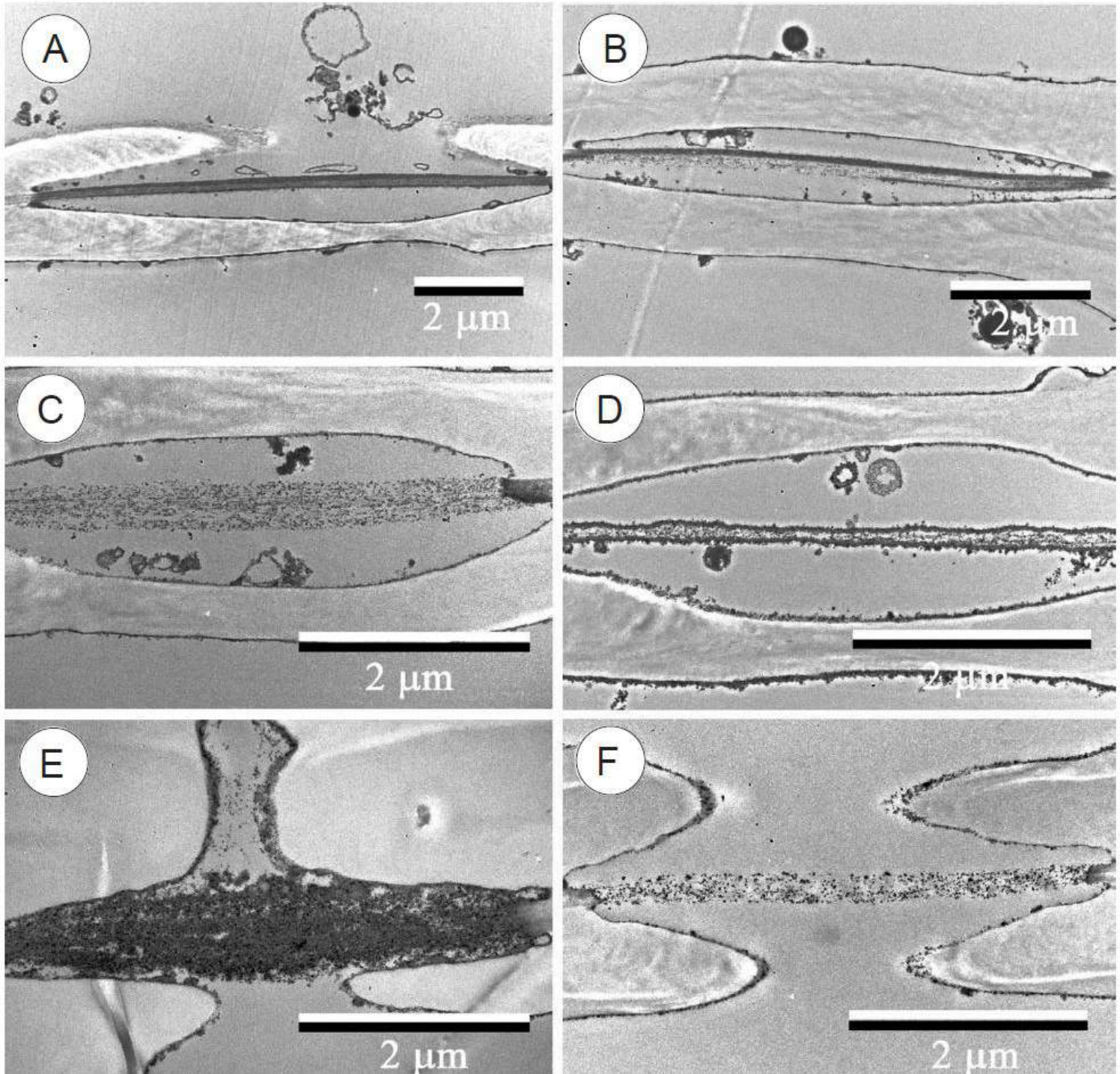
Photo: Jarmila Pittermann

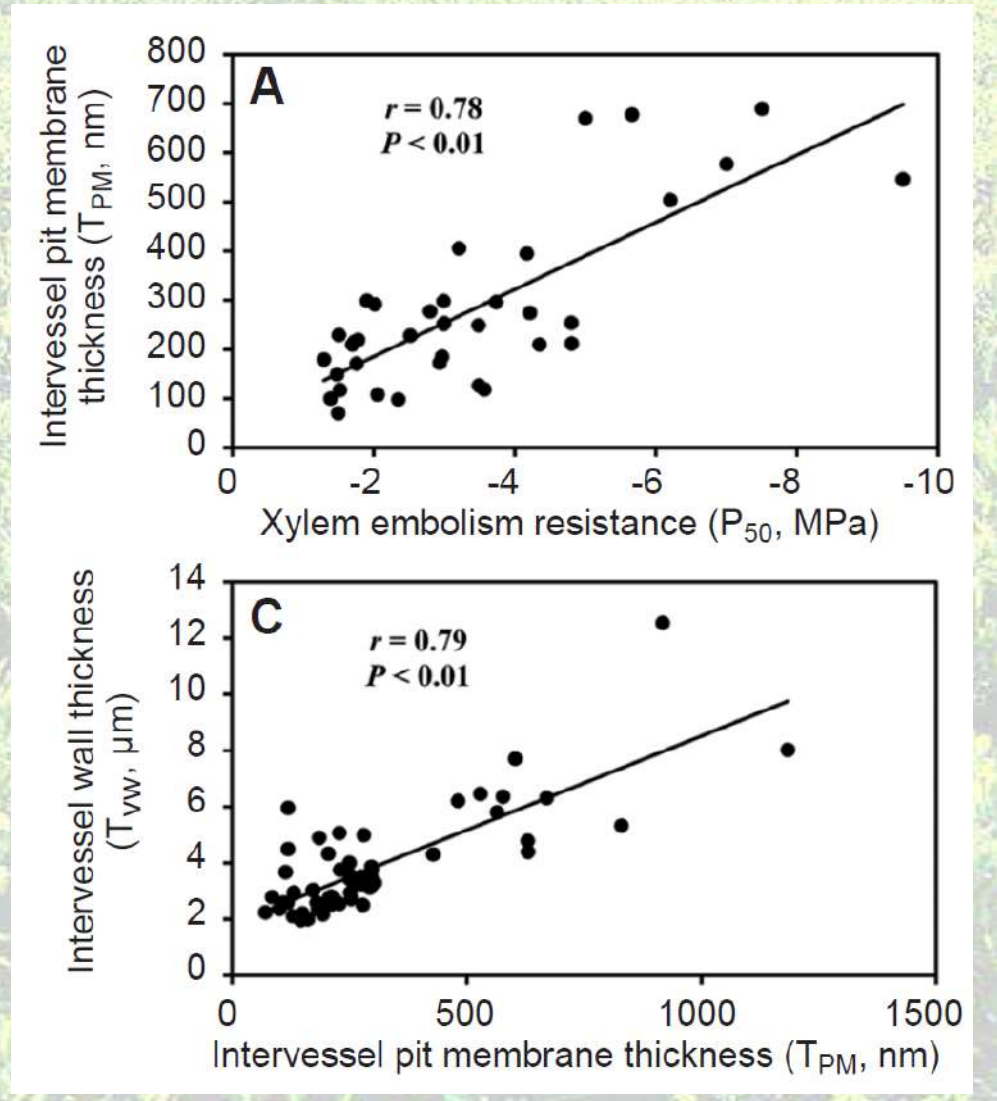


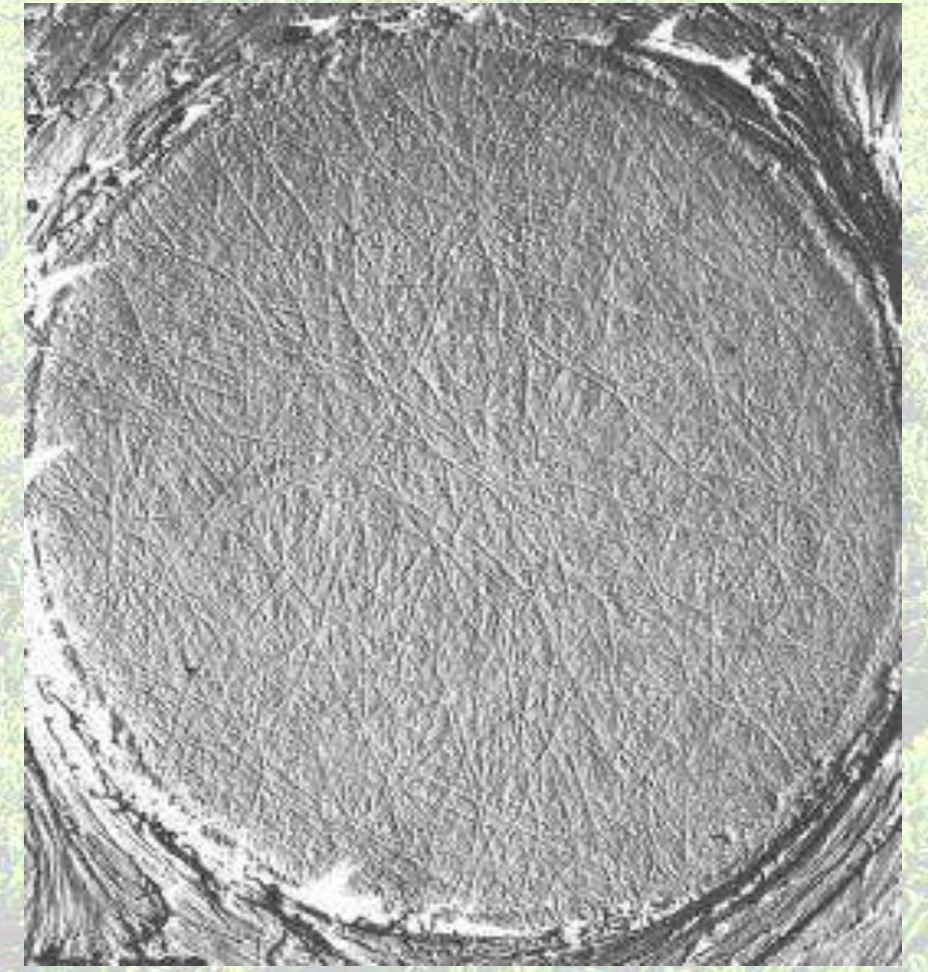
Betula nigra

Photo: Jarmila Pittermann

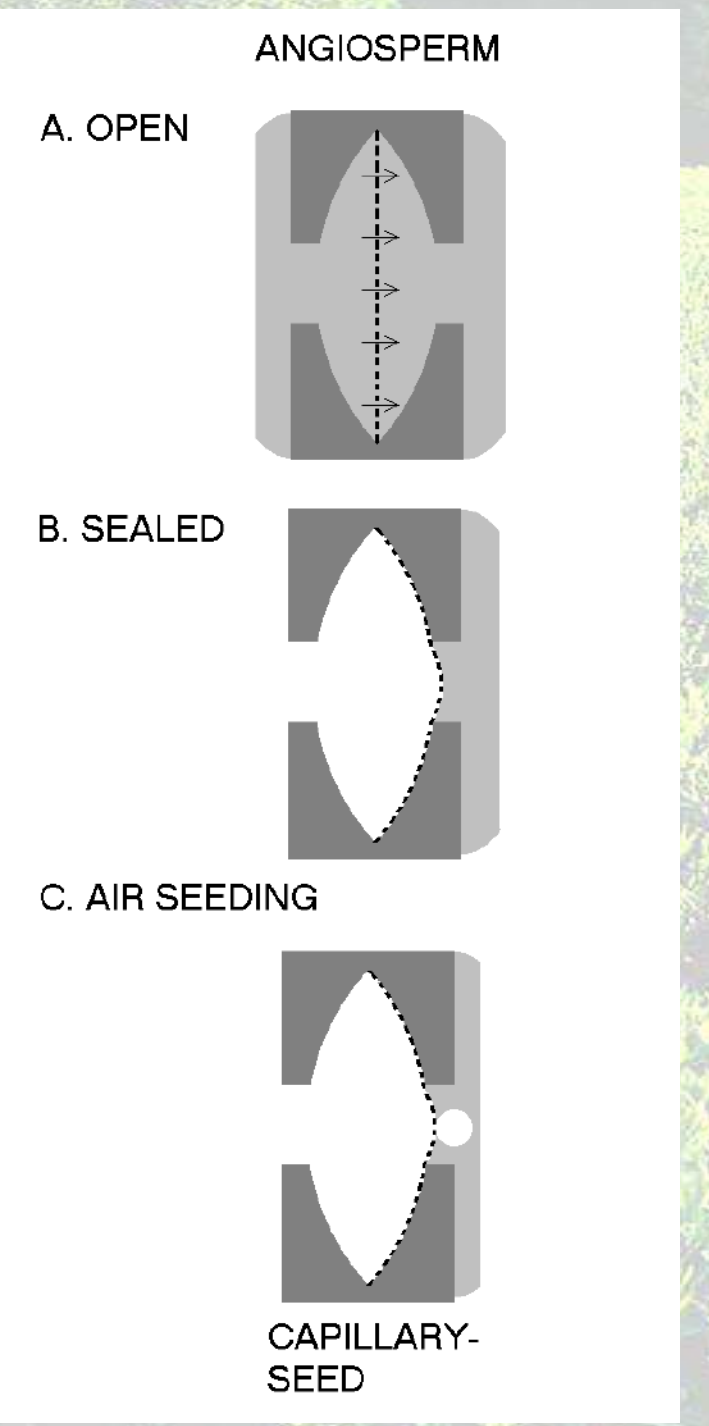

A
3 µm
B
3 µm
C
3 µm
D
1 µm


A
2 μm
B
2 μm
C
2 μm
D
2 μm
E
2 μm
F
2 μm

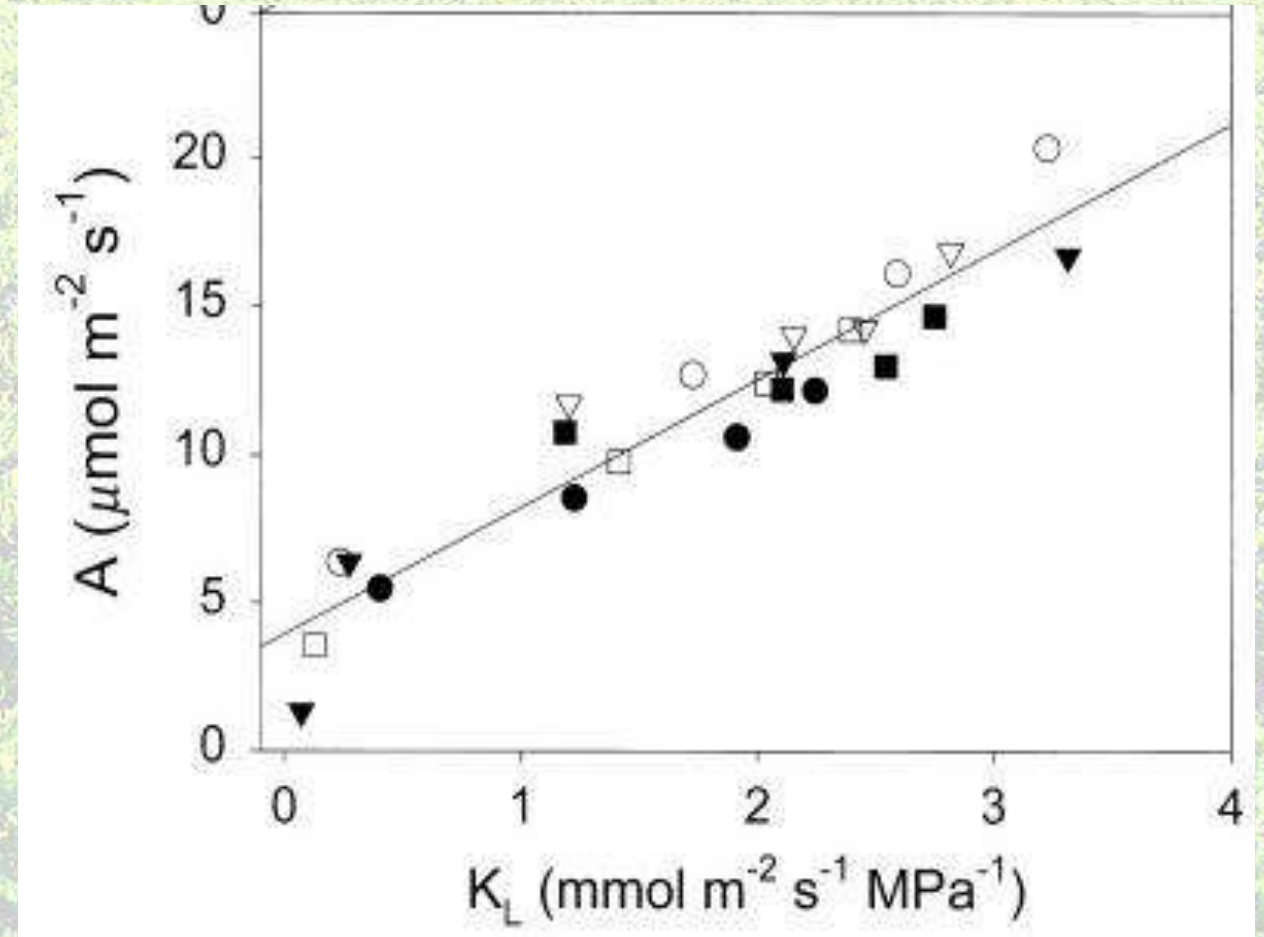

A
r = 0.78
P < 0.01
Intervessel pit membrane thickness (T_PM, nm)
800
700
600
500
400
300
200
100
0
0
-2
-4
-6
-8
-10
Xylem embolism resistance (P50, MPa)
C
r = 0.79
P < 0.01
Intervessel wall thickness (T_VW, μm)
14
12
10
8
6
4
2
0
0
500
1000
1500
Intervessel pit membrane thickness (T_PM, nm)

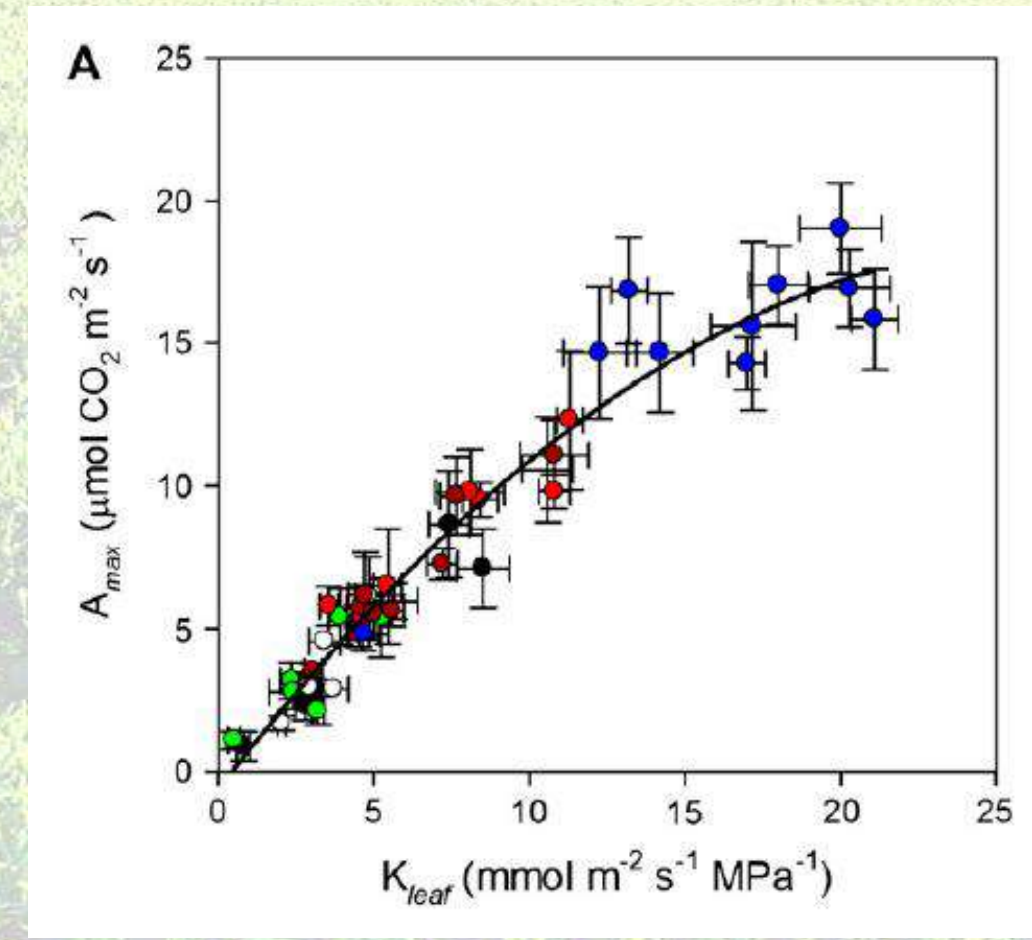


Hacke, Sperry and Pittermann 2004



High hydraulic efficiency to grow more





Hubbard, Ryan, Stiller & Sperry 2001

Brodribb et al, 2007



Since hydraulic conductance is so important, why not all species have a high capacity and a high resistance to cavitation?



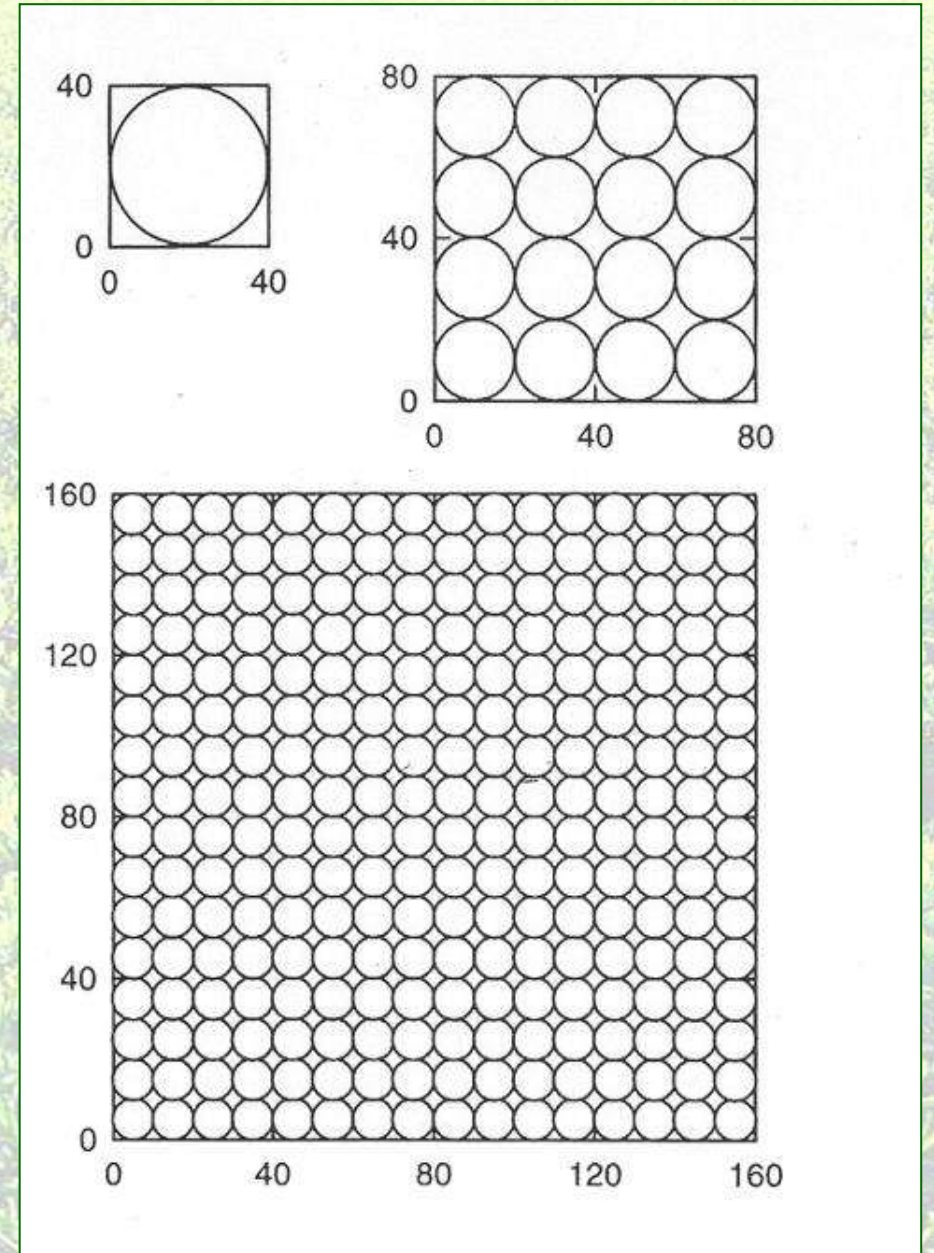
Water transport

The conductivity of a vessel depends much of the vessel diameter:

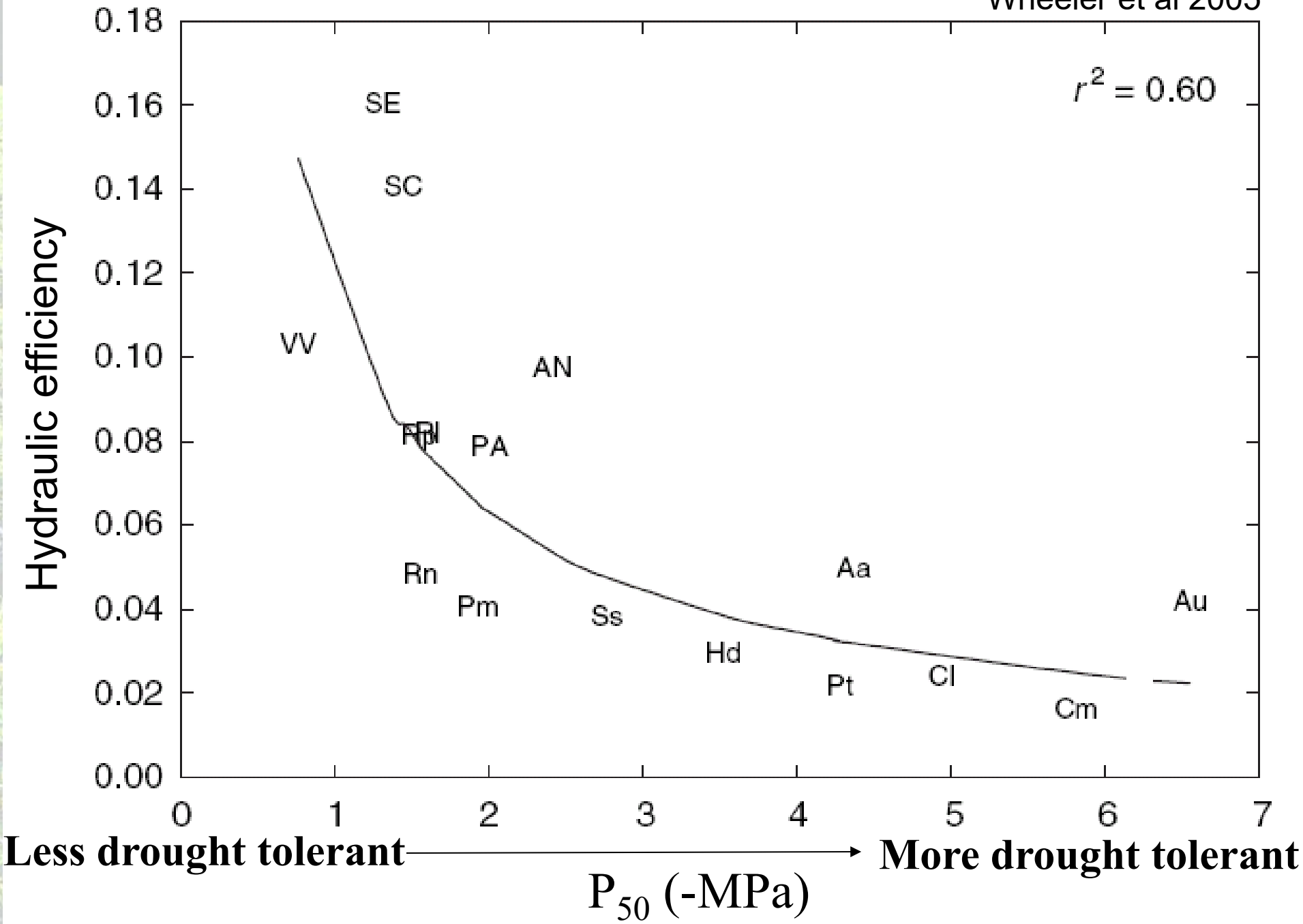
Hagen-Poiseuille Law:

$$\textbf{Flujo } (q) = (\pi r^4 / 8 l \eta) \Delta \Psi_p$$

q water flow
r vessel radius
η water viscosity
l vessel lenght
$\Delta \Psi_p$ pressure gradient

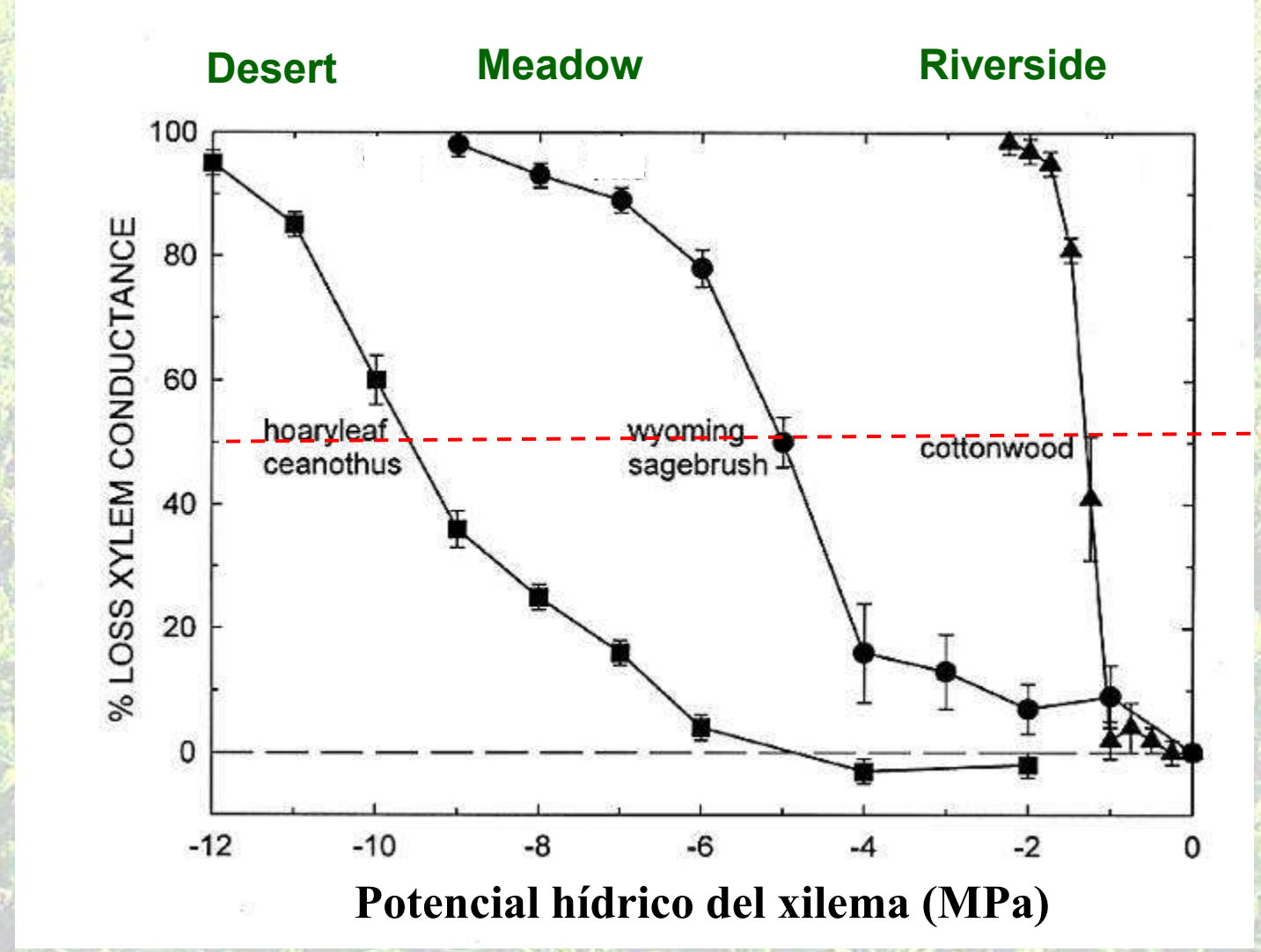


Wheeler et al 2005



Water transport

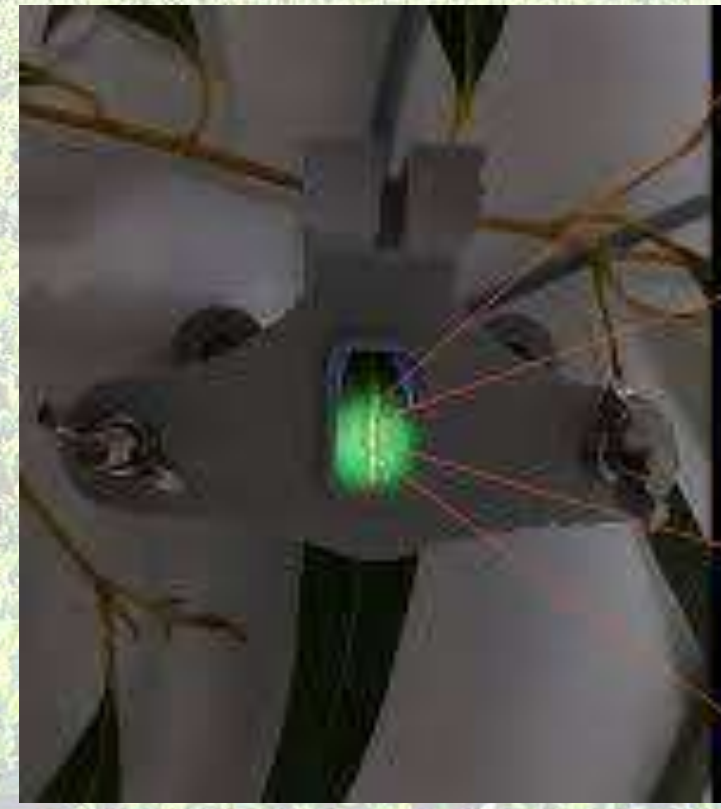
Vulnerability curves of different species in different habitats

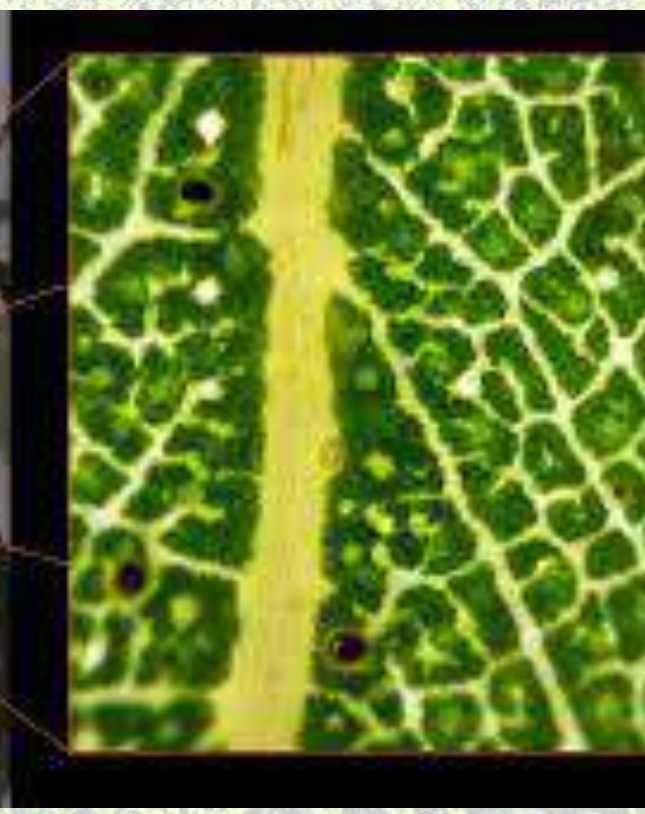


Kolb and Sperry 1999

Water transport



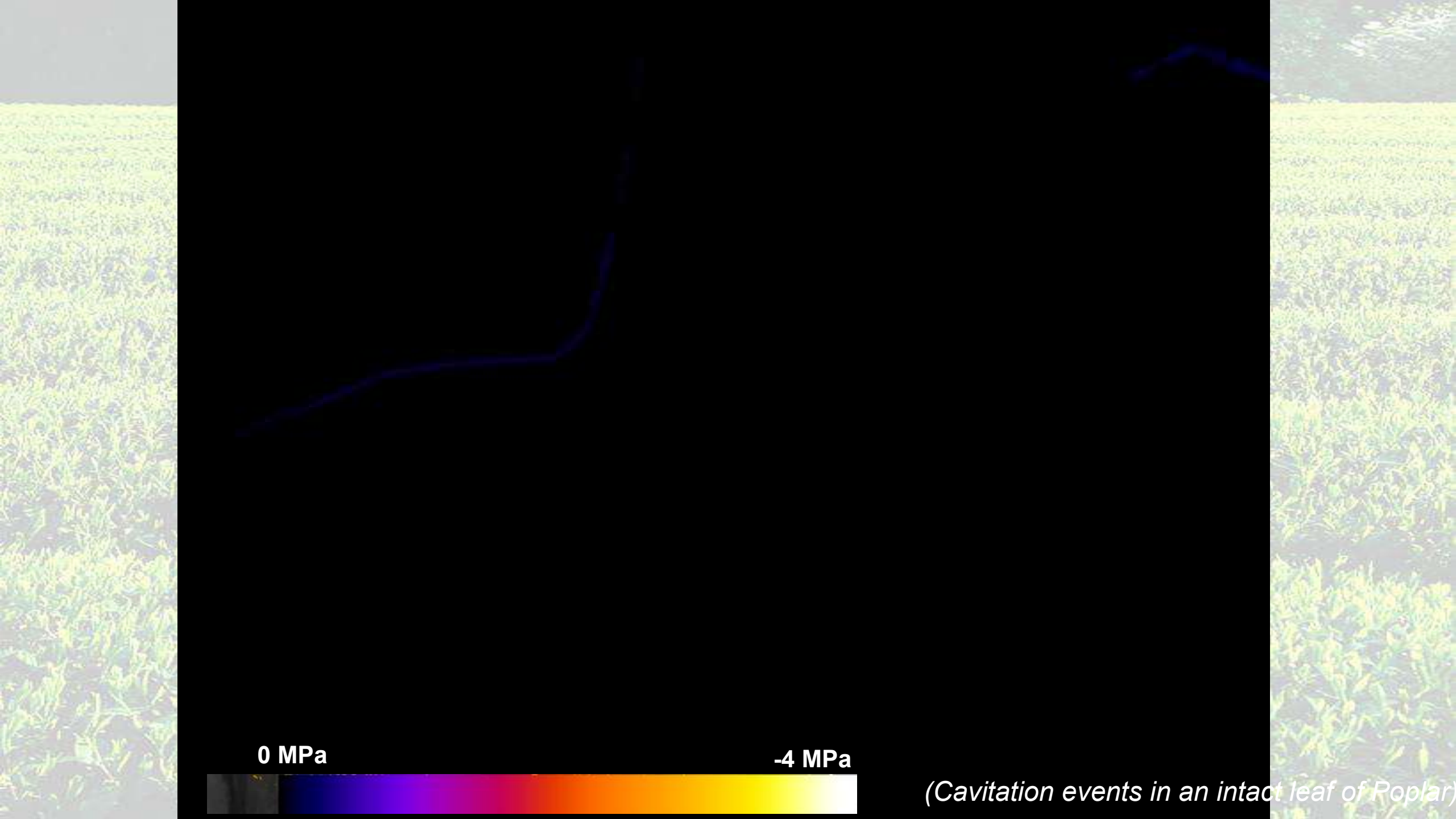




Water transport

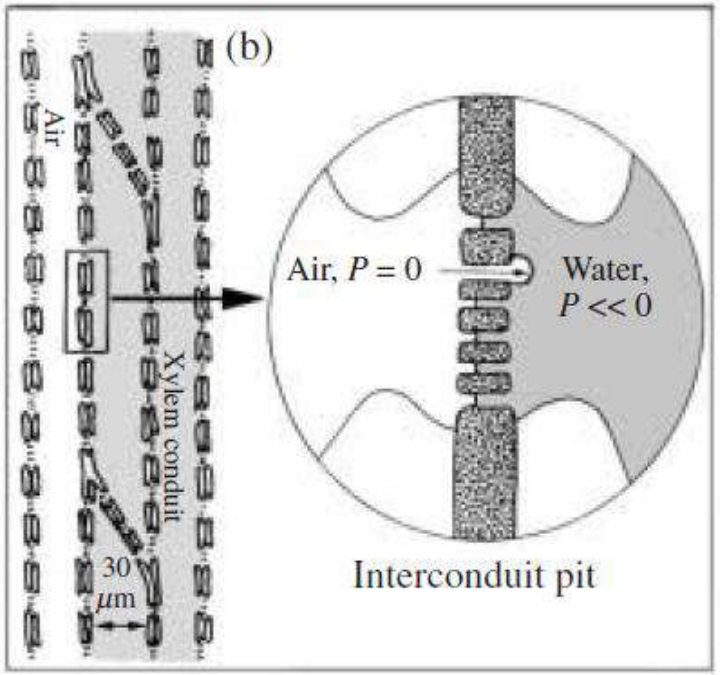
"C:\Users\antonio\Nextcloud\Documentos\Congresos\Congresos 2018\OlivebioTeq\Charla Antonio\Celia\Combined Stacks stem.avi"

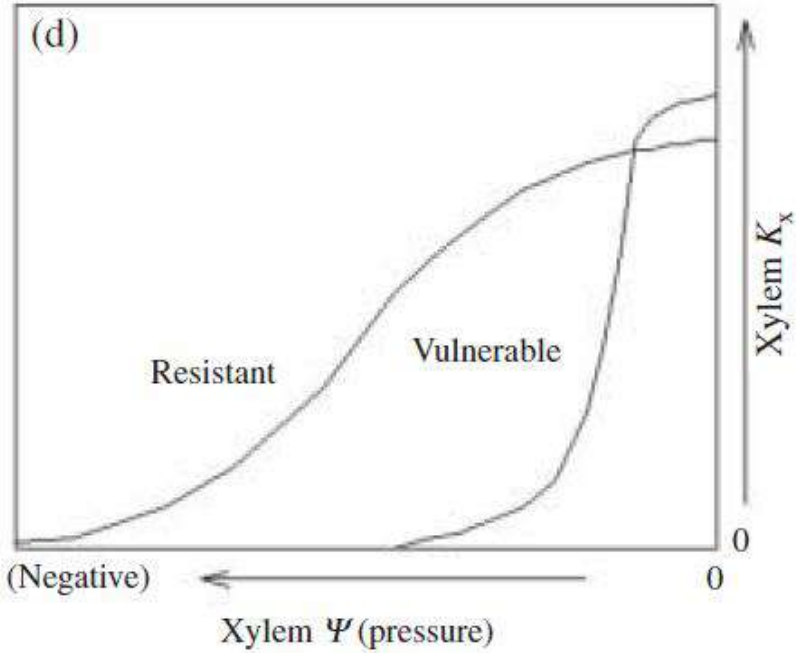
"D:\Presentaciones Antonio\Combined Stacks stem.avi"



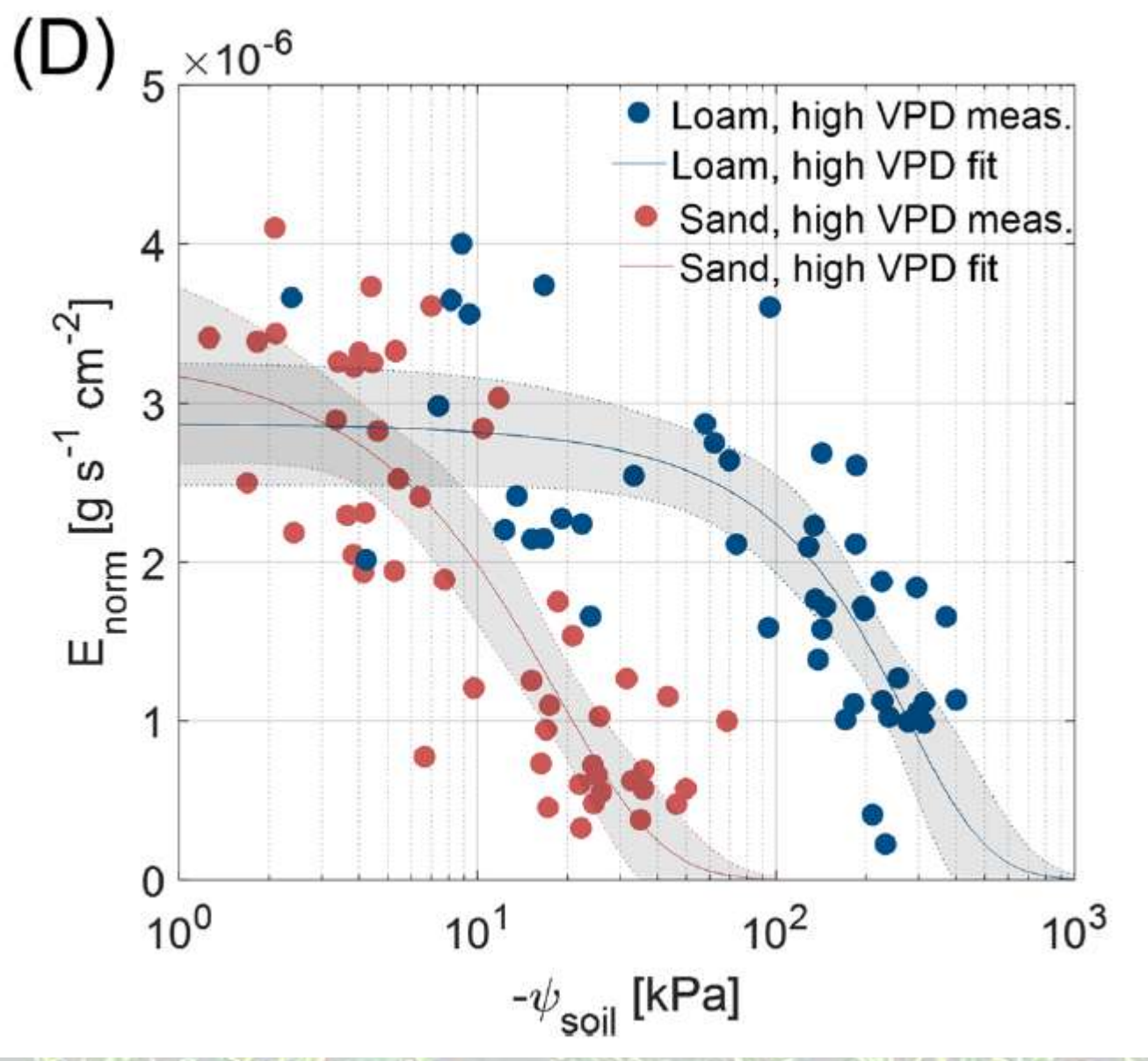
(Cavitation events in an intact leaf of Poplar)

Water transport





Soil texture effect on transpiration



doi:10.1093/plphys/kiab271 PLANT PHYSIOLOGY 2021: 187: 858–872

Plant Physiology®

Soil textures rather than root hairs dominate water uptake and soil–plant hydraulics under drought

Gaochao Cai [1,2] Andrea Carminati,[3] Mohanned Abdalla [1] and Mutez Ali Ahmed [1,2,*,†]

Research

New Phytologist

Rapid report

Declining root water transport drives stomatal closure in olive under moderate water stress

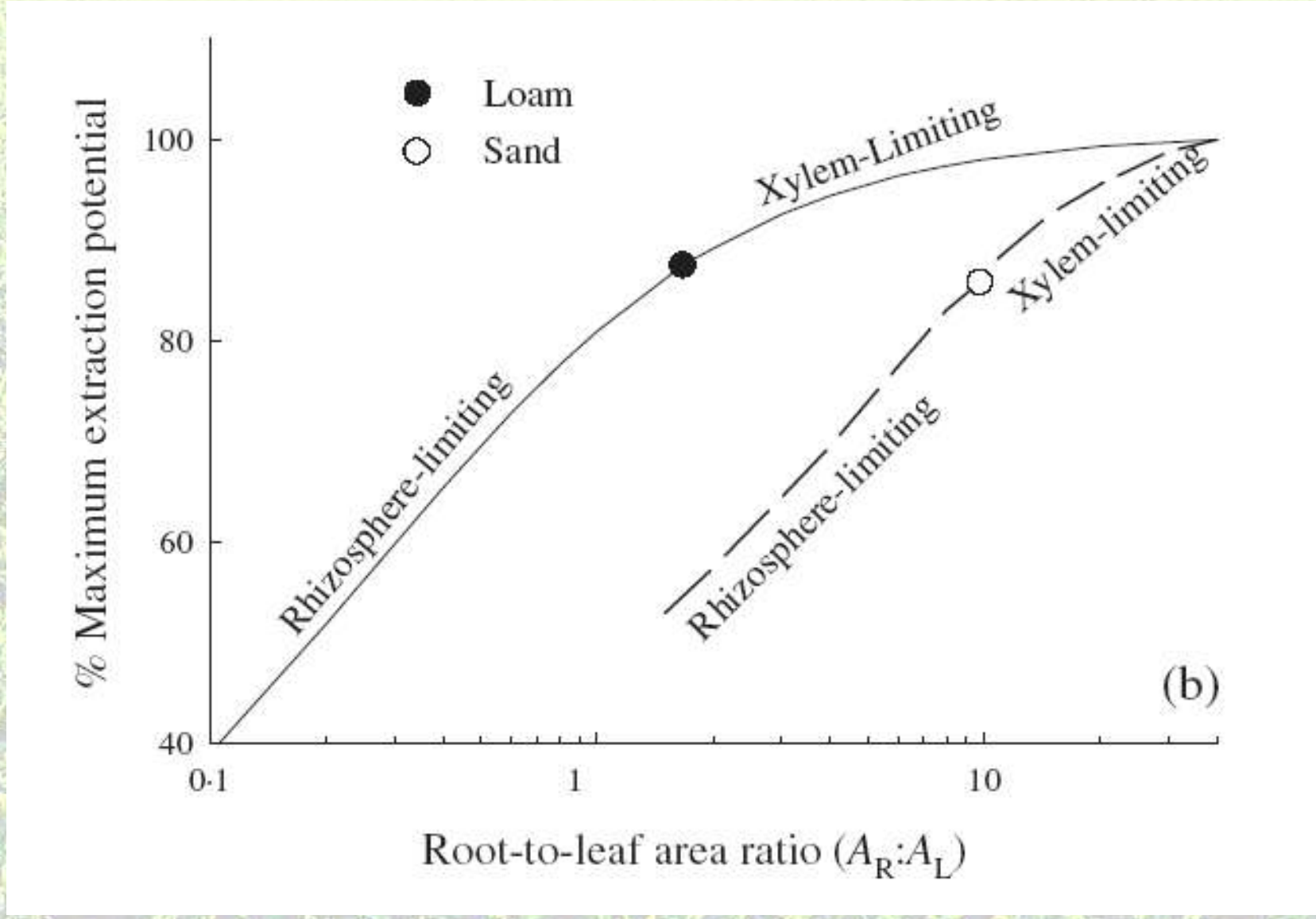
Author for correspondence:
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Tel: +61 3 6226 2647
Emails: cmrdominguez@gmail.com

Received: *10 June 2019*
Accepted: *1 September 2019*

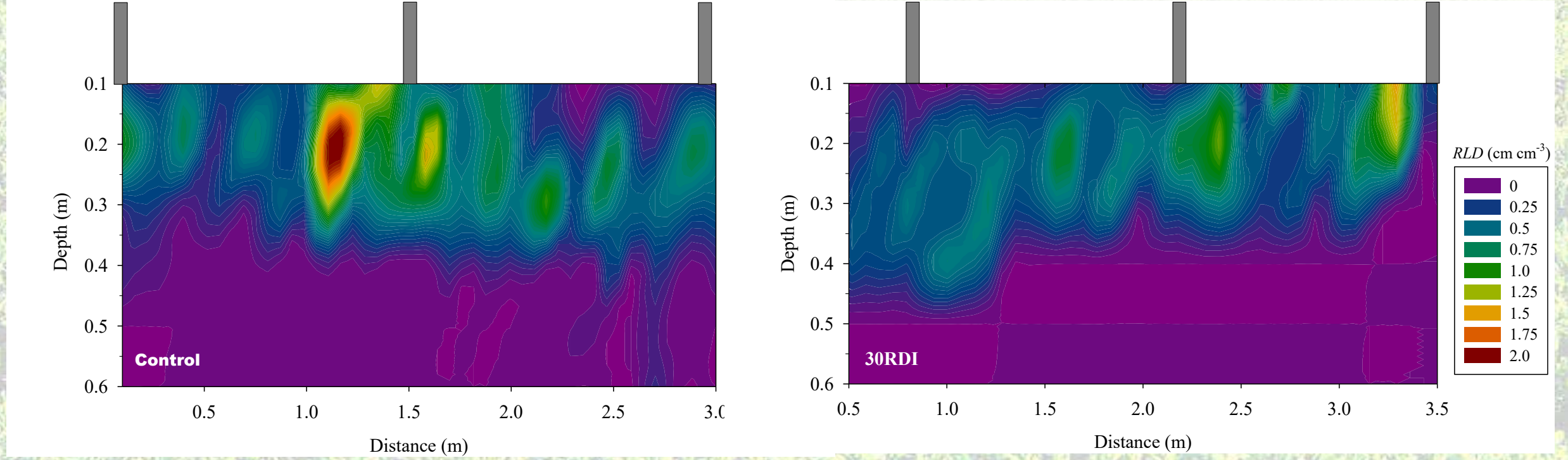
Celia M. Rodriguez-Dominguez[1,2] and Timothy J. Brodribb[2]

[1]Irrigation and Crop Ecophysiology Group, Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC), Avenida Reina Mercedes, 10, 41012, Sevilla, Spain; [2]School of Biological Sciences, University of Tasmania, Private Bag 55, Hobart, TAS 7001, Australia

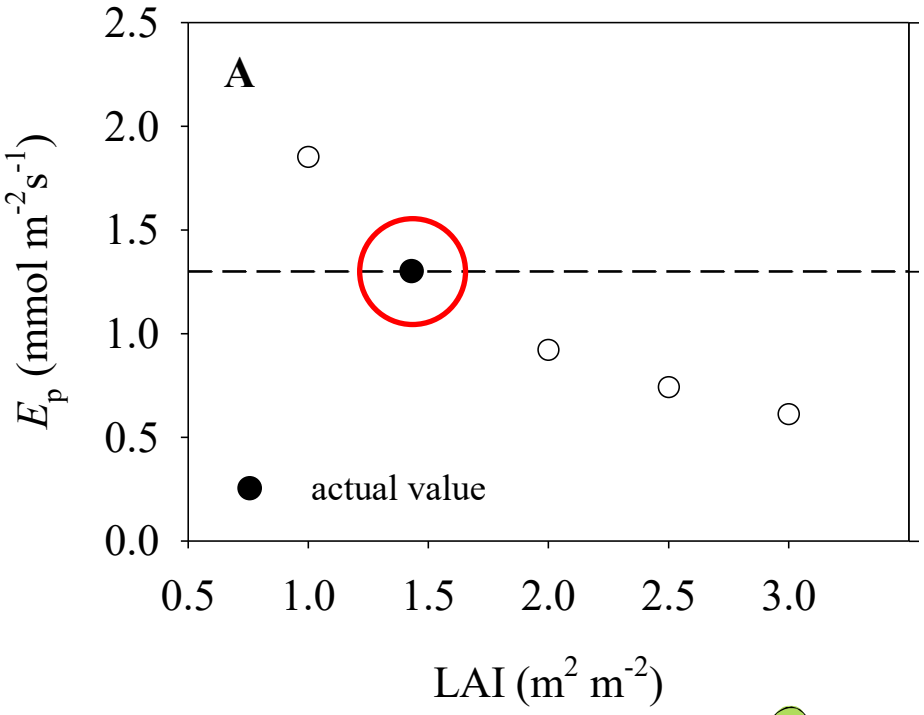
Effect of limiting root area

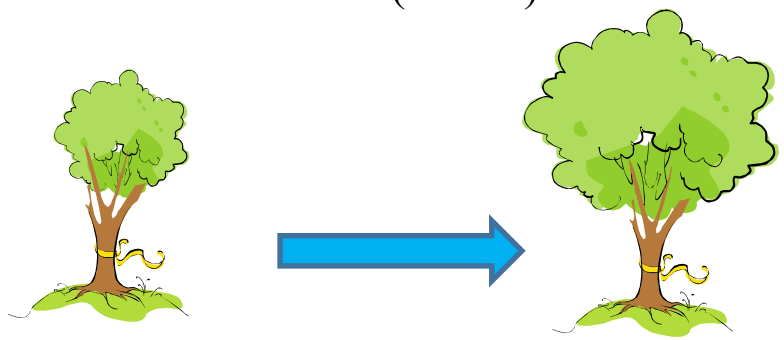


Root distribution

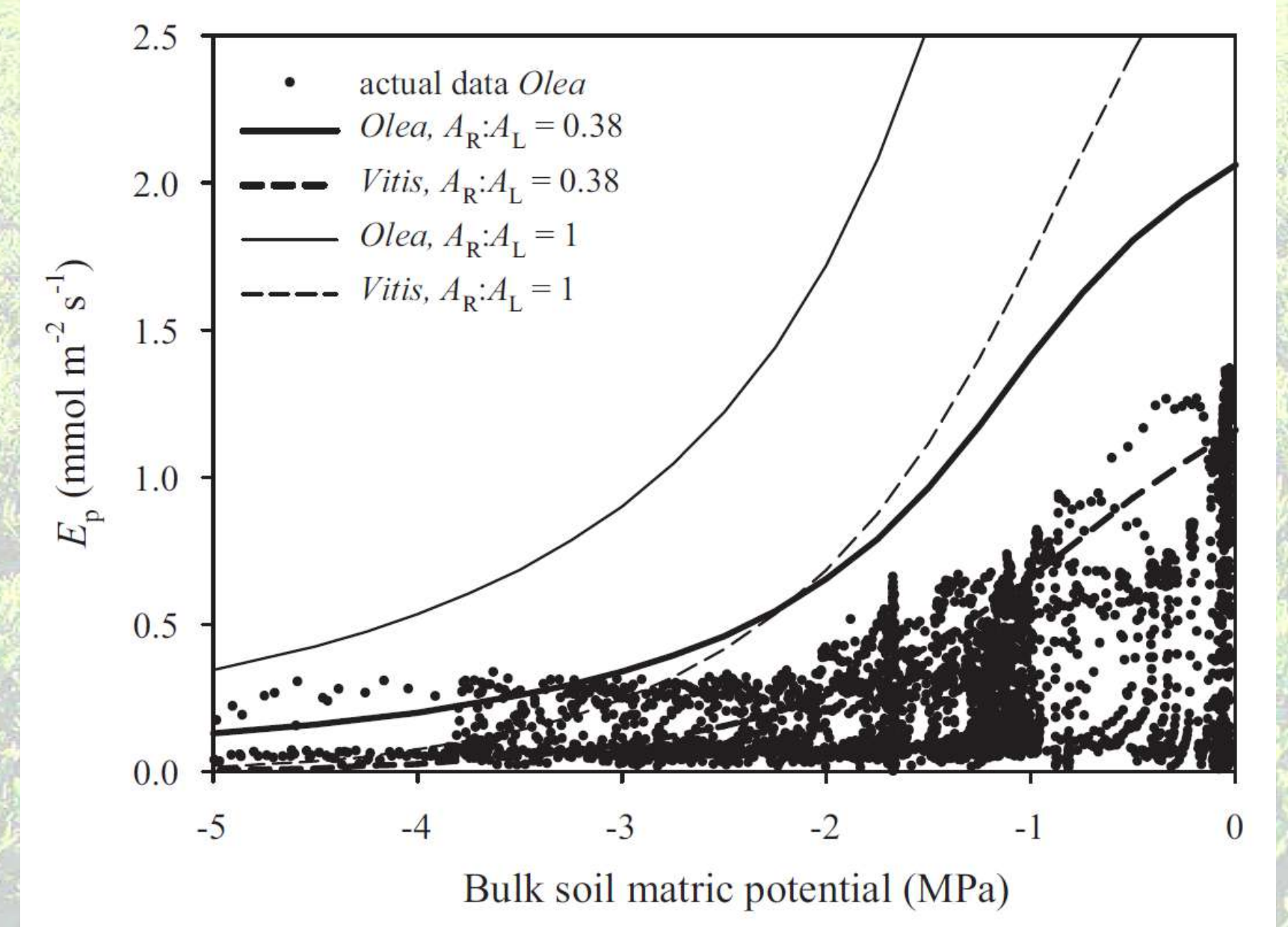


Tree size and number of drippers

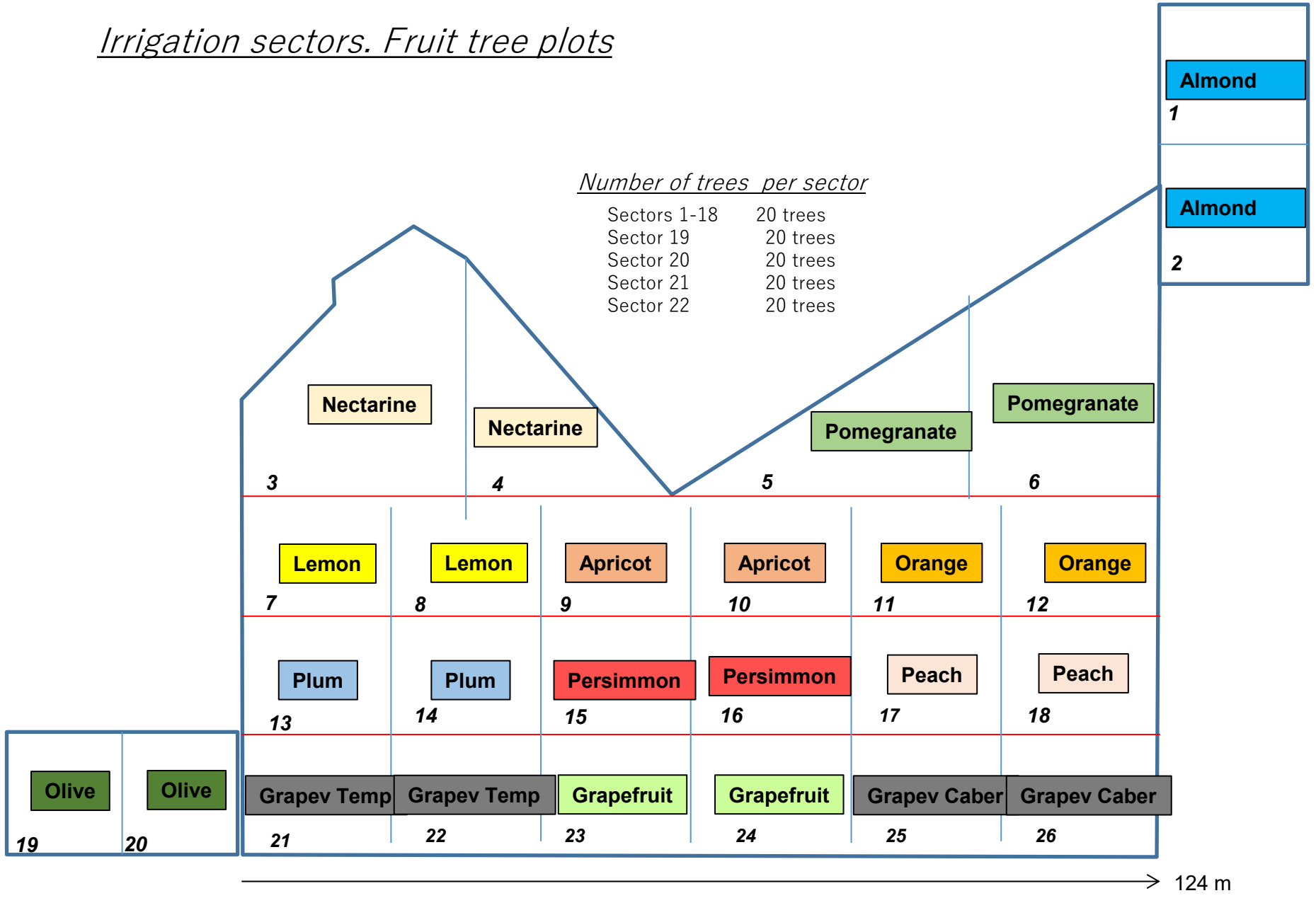




Limitations by the root:leaf área ratio

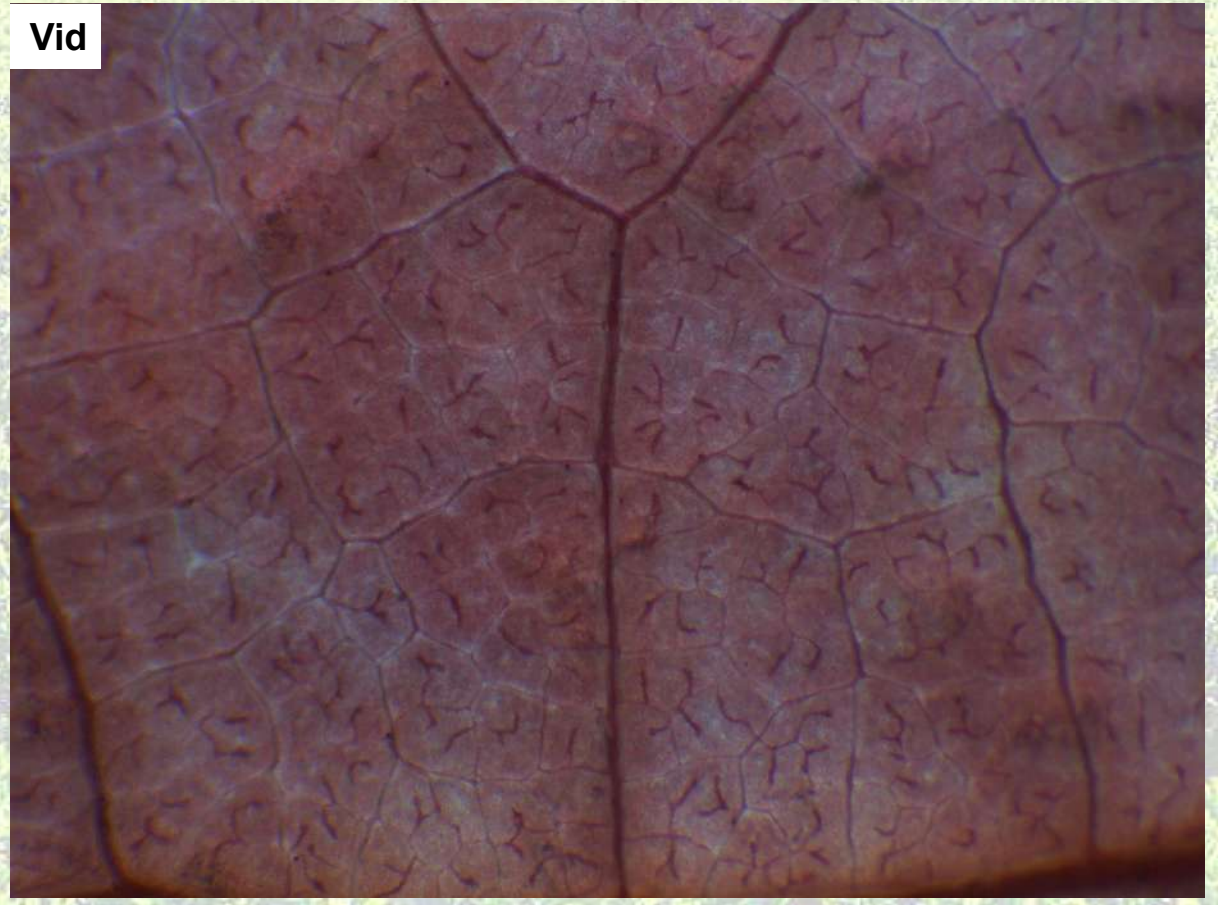


Irrigation sectors. Fruit tree plots



Leaf vein density



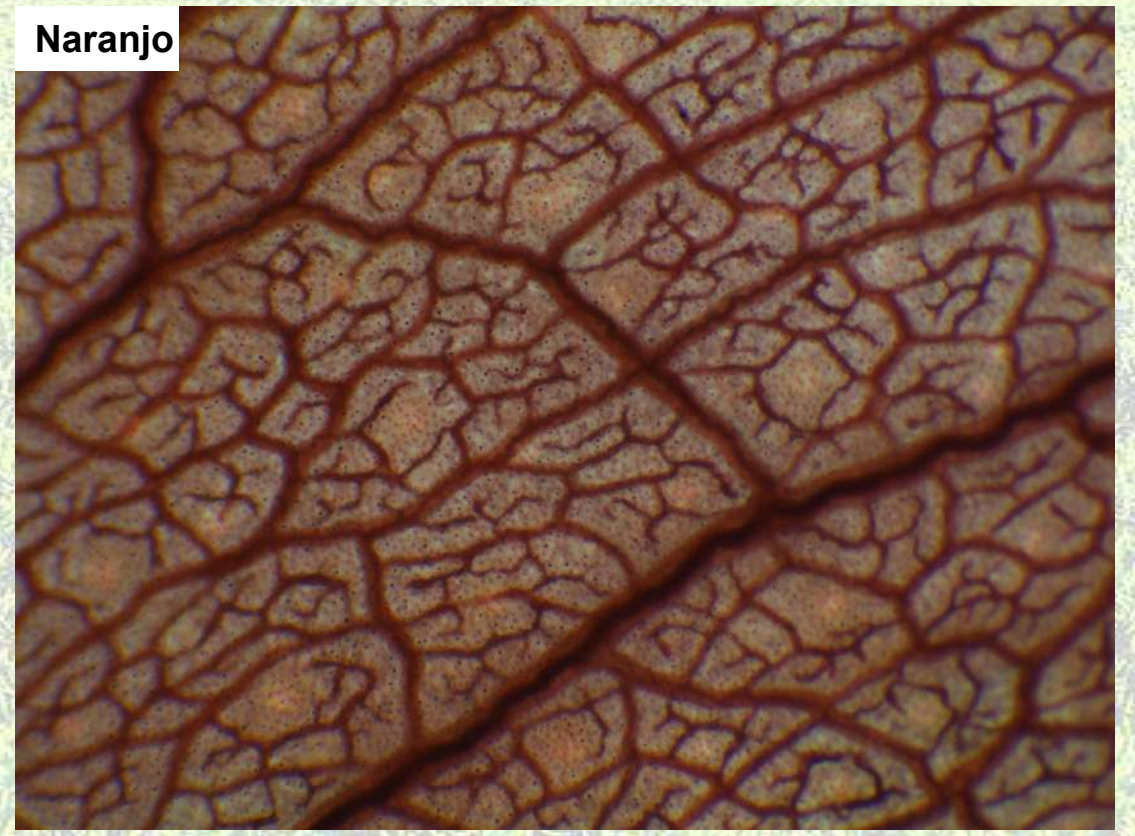


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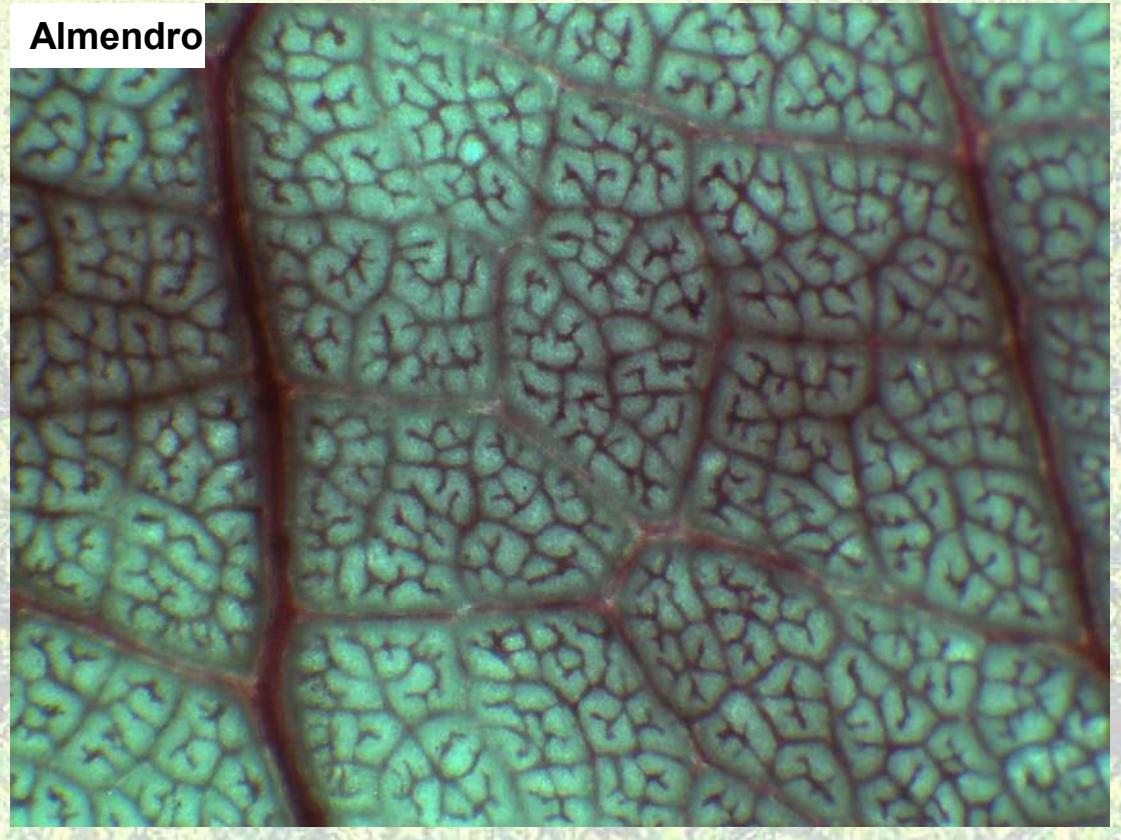
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Leaf vein density

Naranjo



Almendro

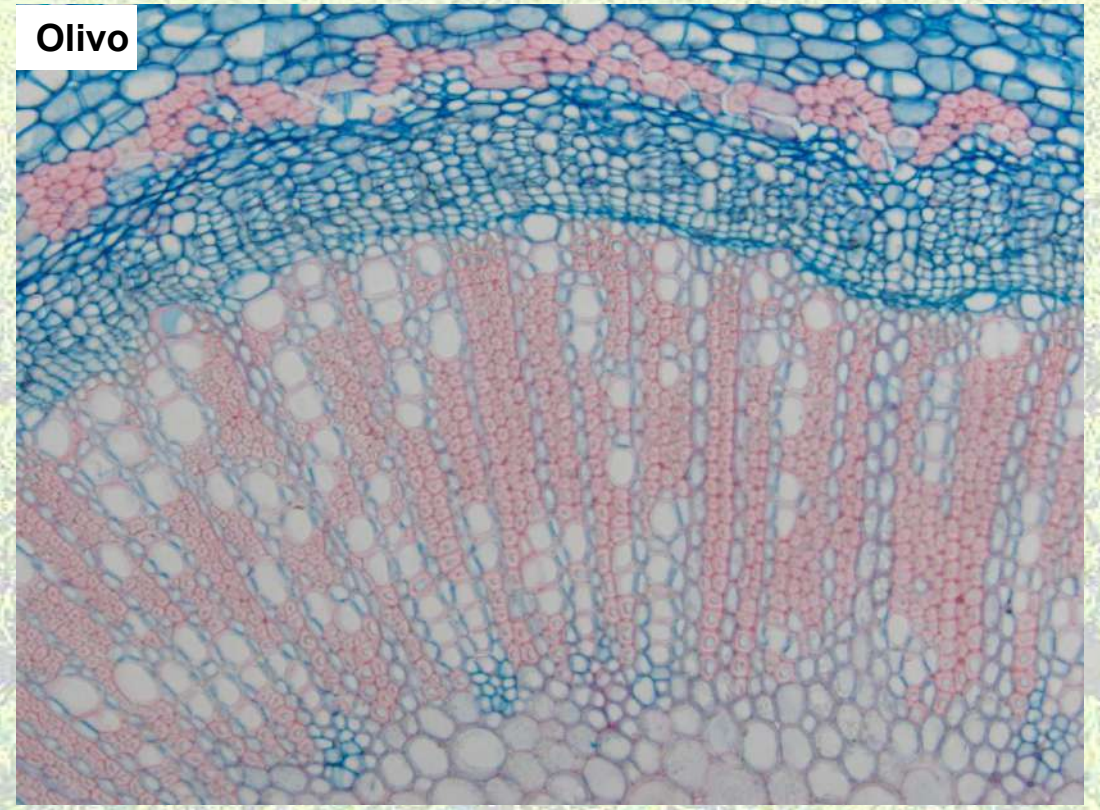


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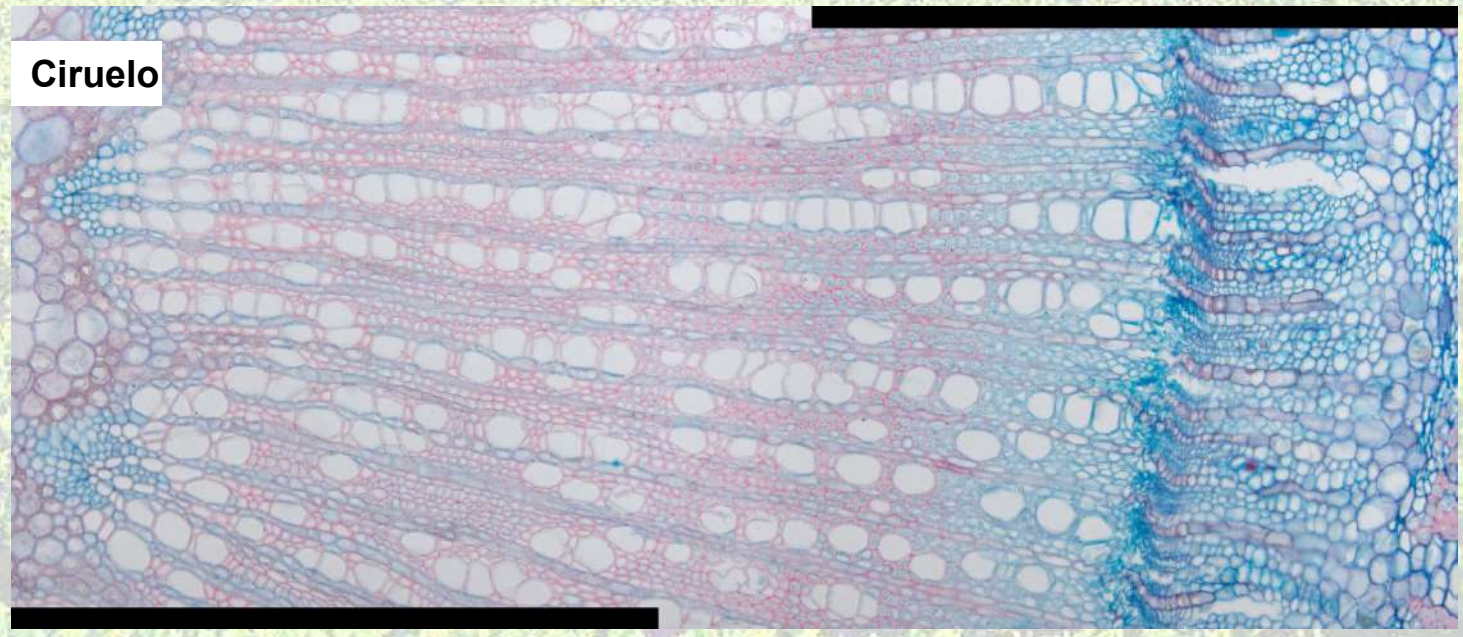
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Xylem

Olivo



Ciruelo

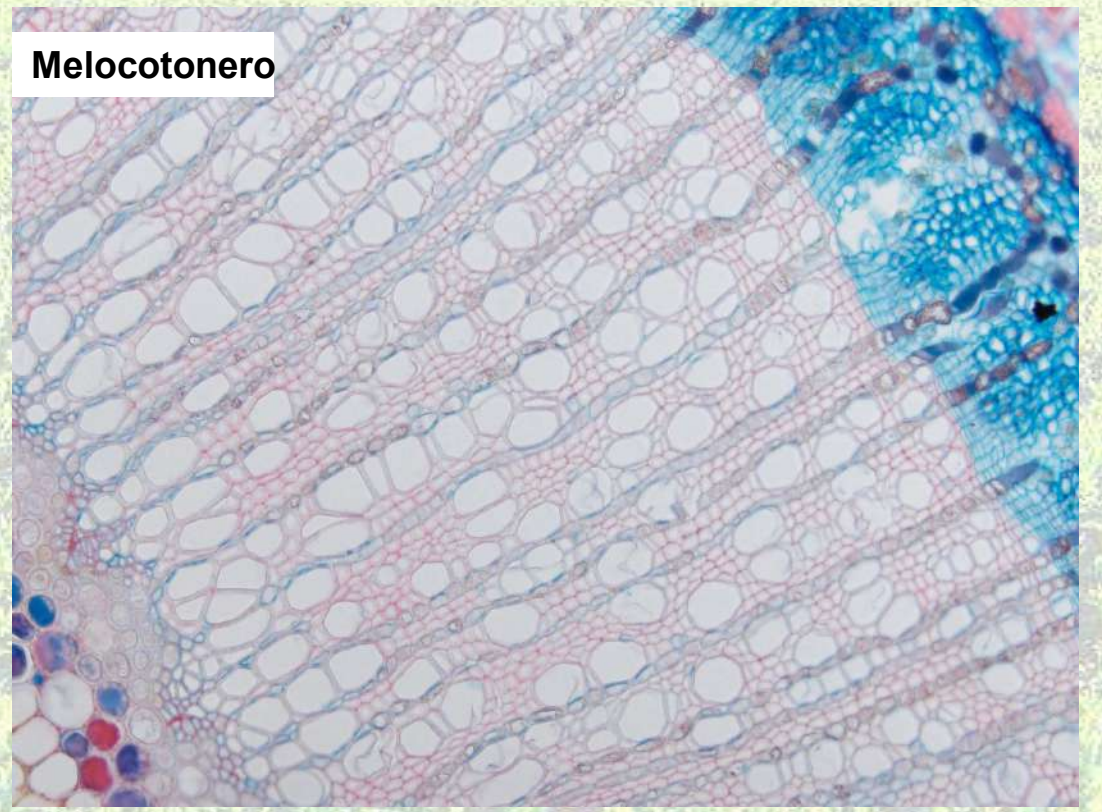


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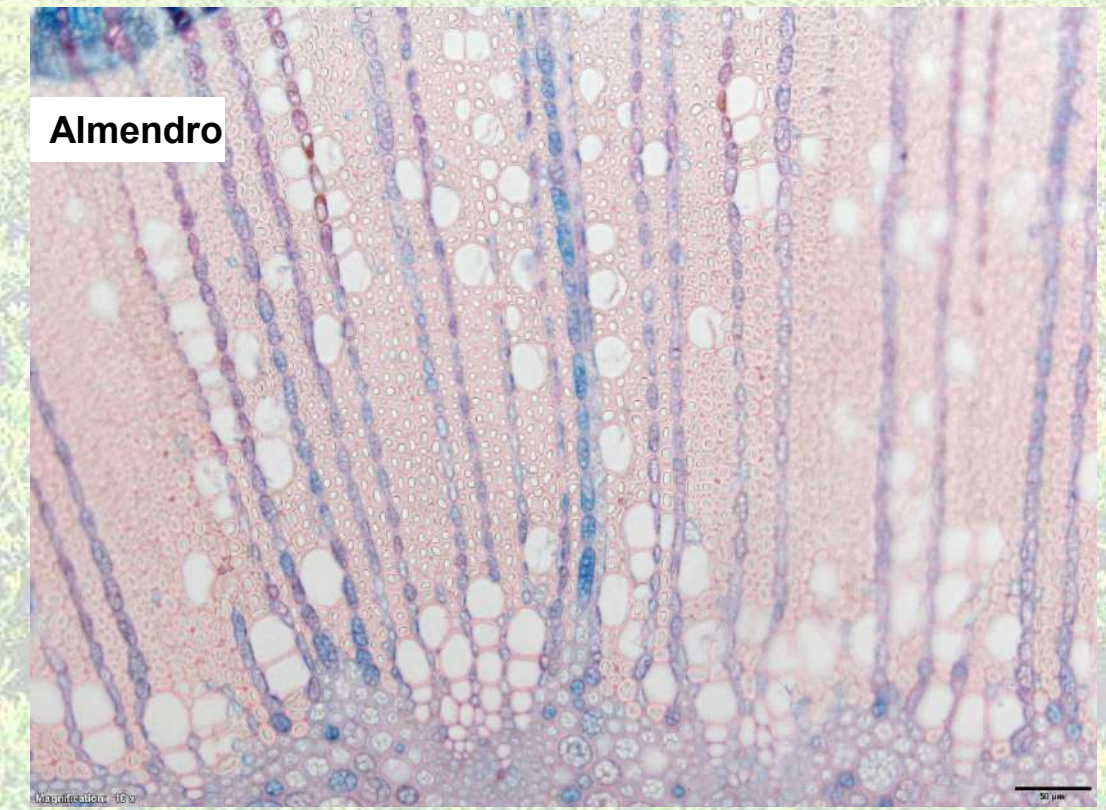
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Xylem

Melocotonero



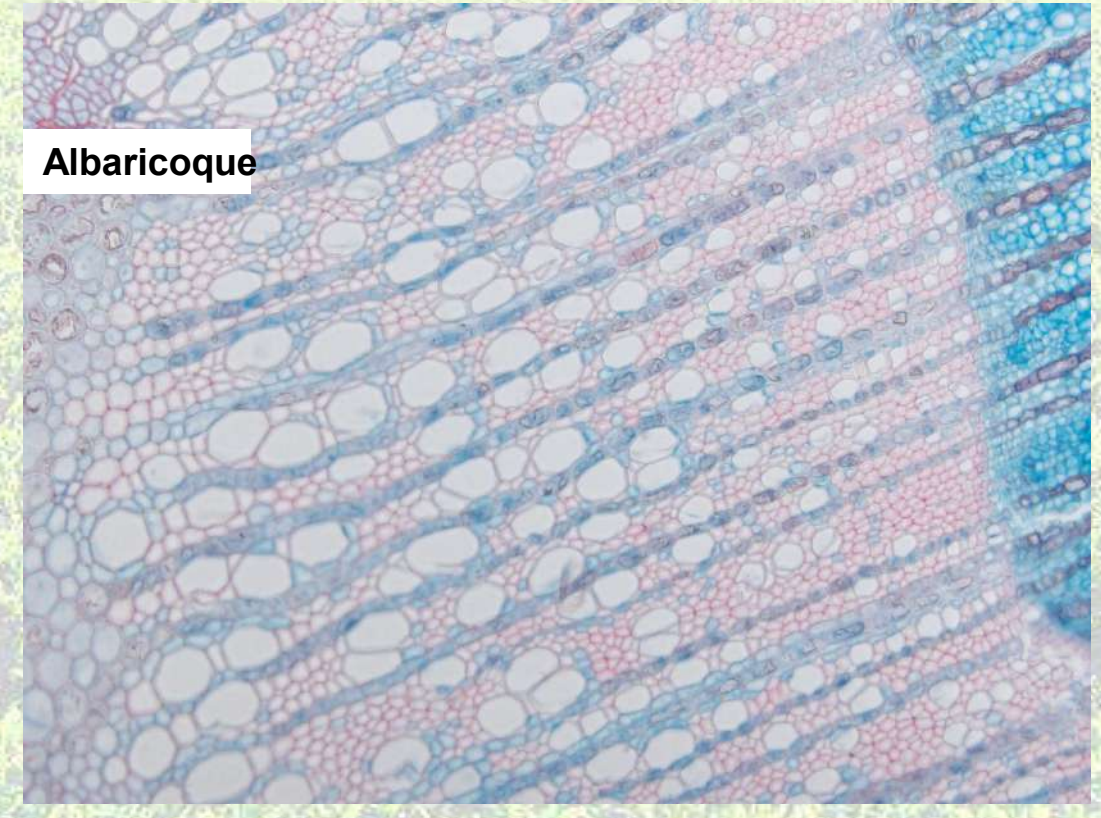
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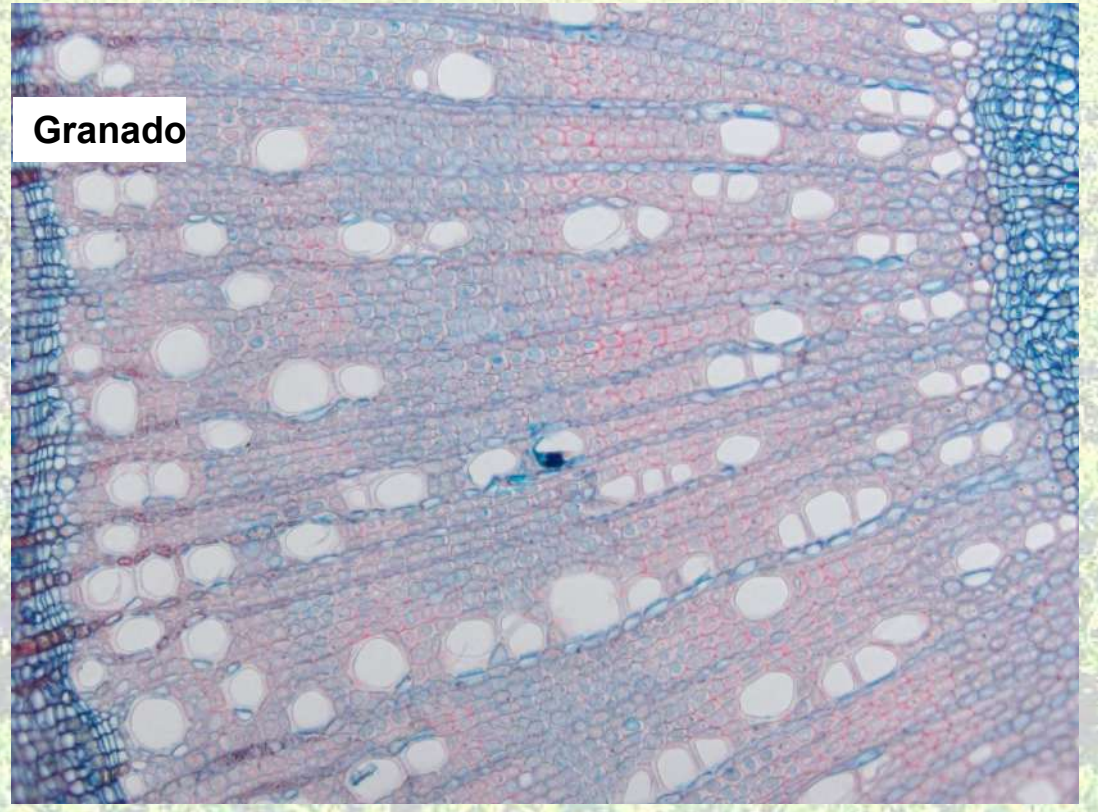


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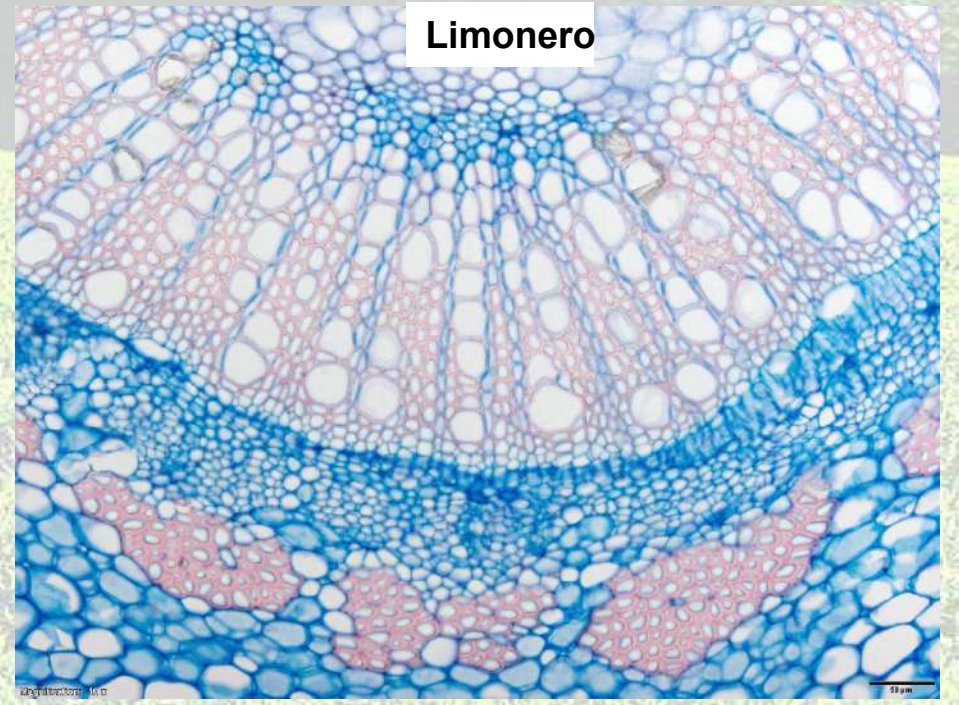
Xylem



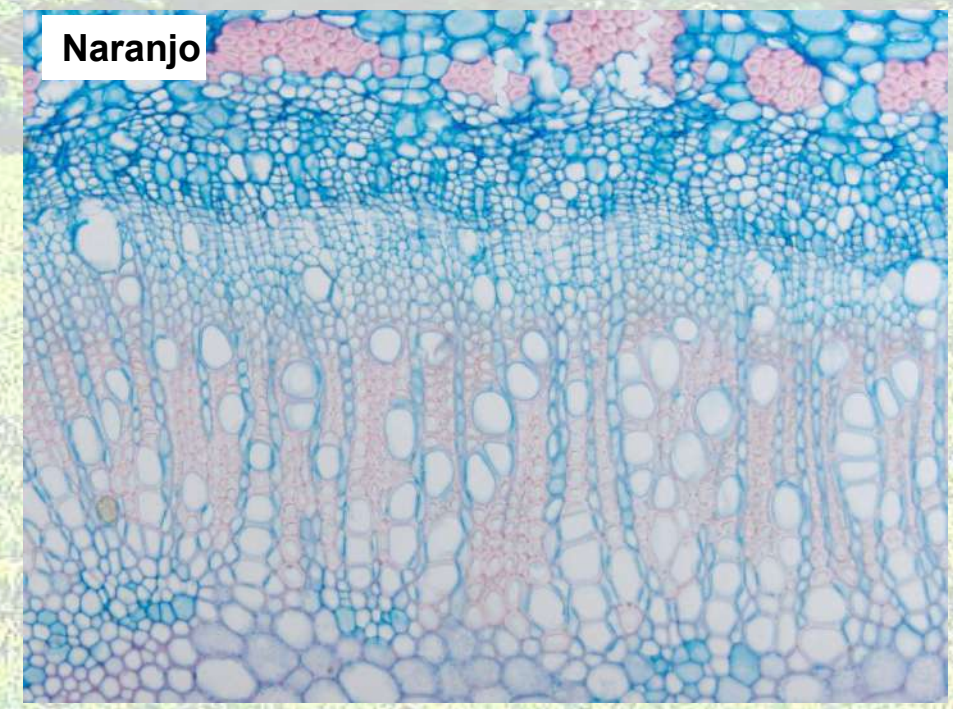


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Limonero



Naranjo



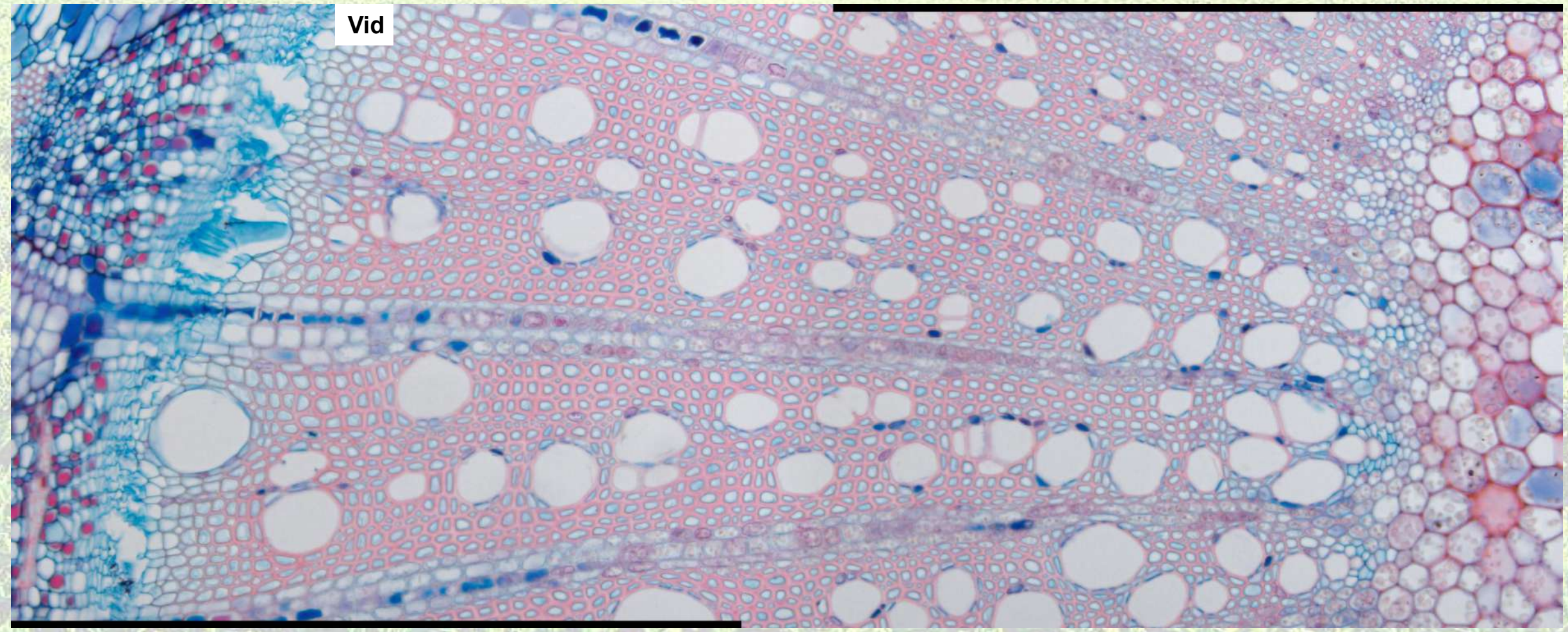
Pomelo



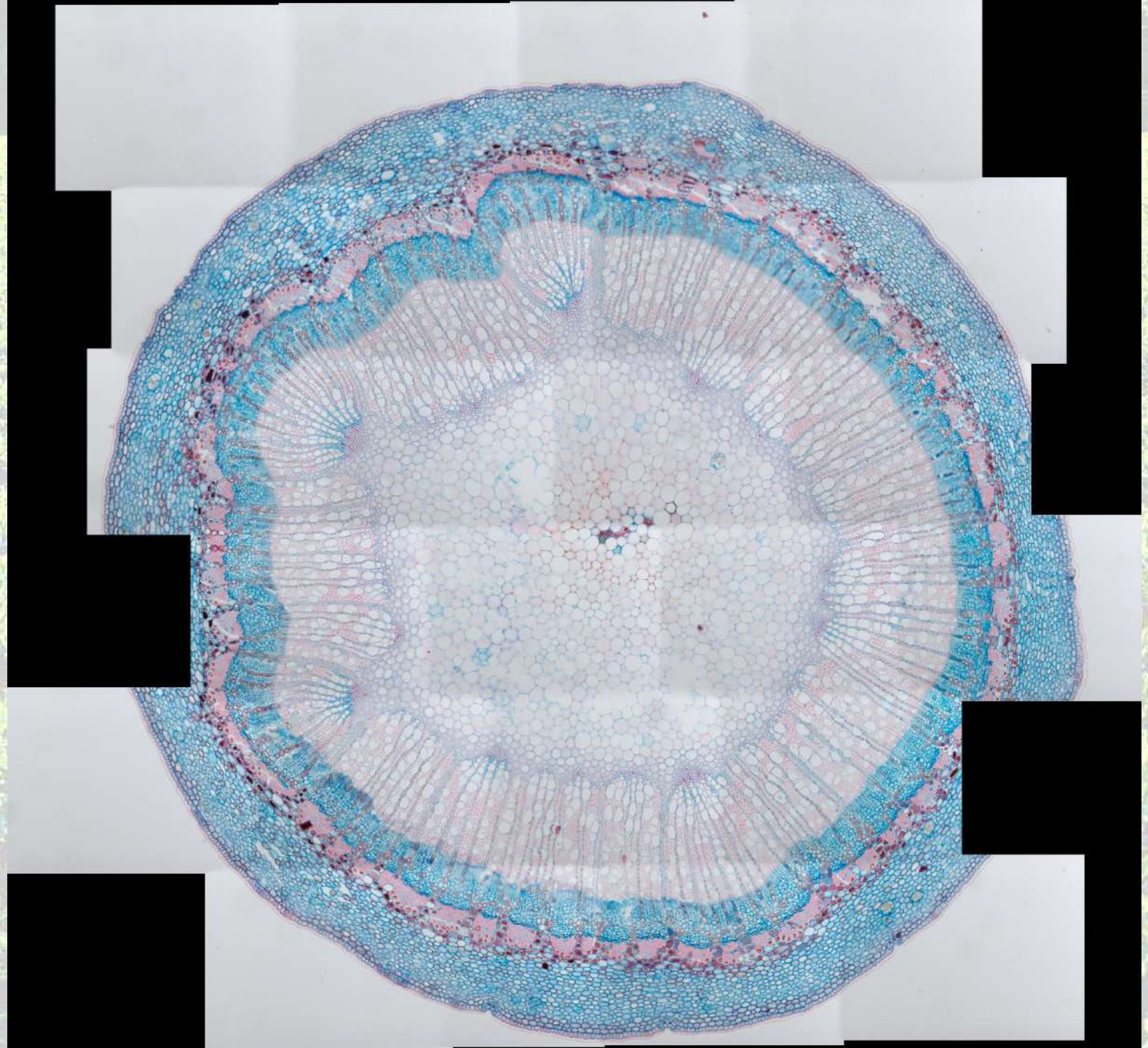
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Xylem



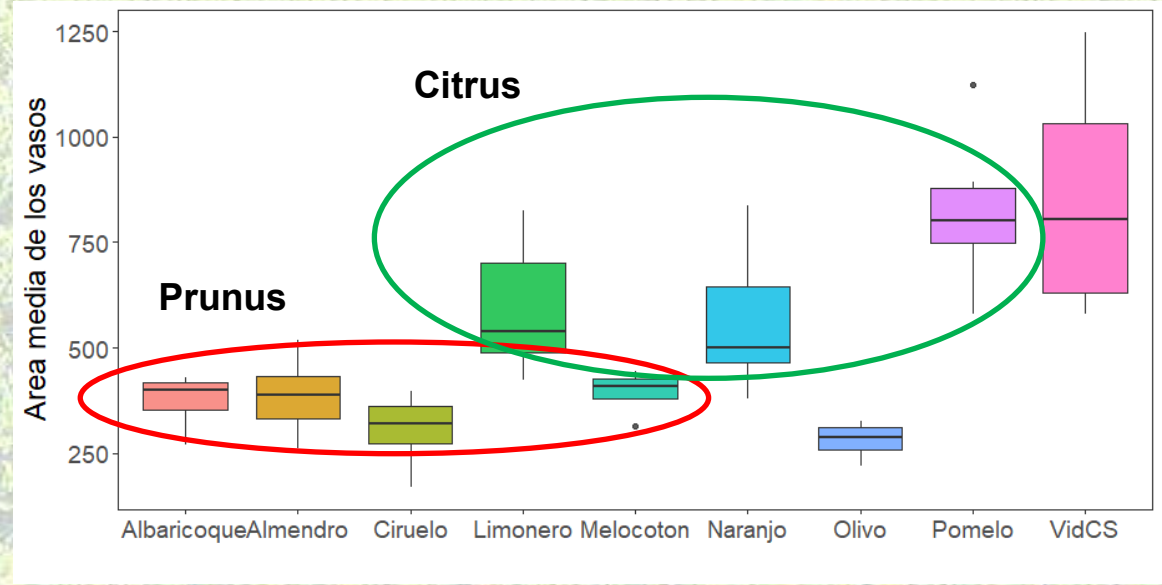
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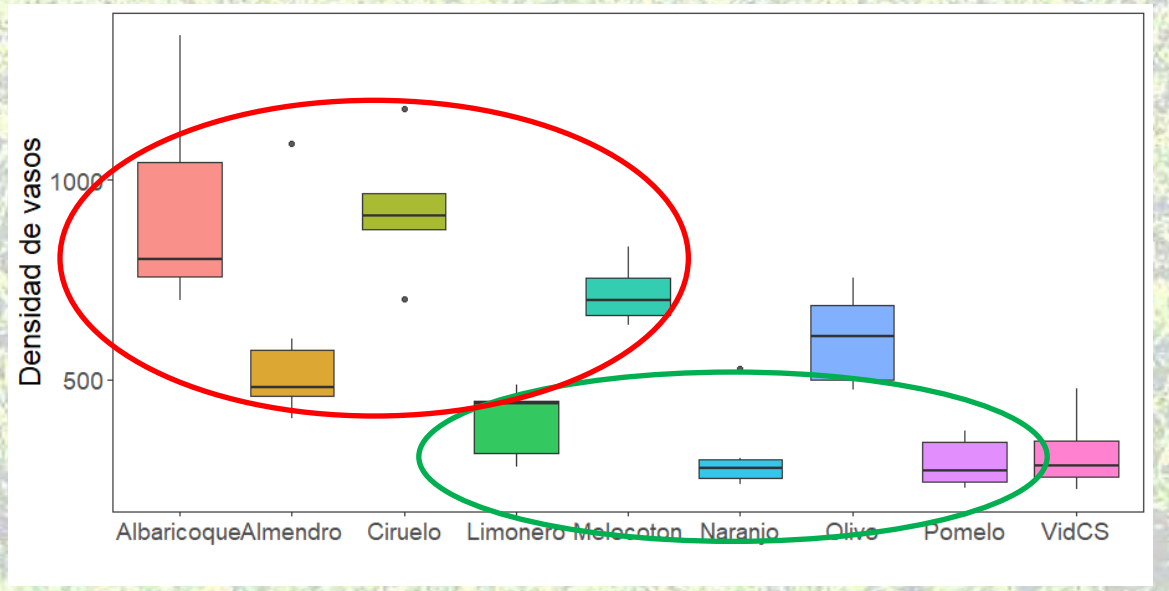


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Physiological traits

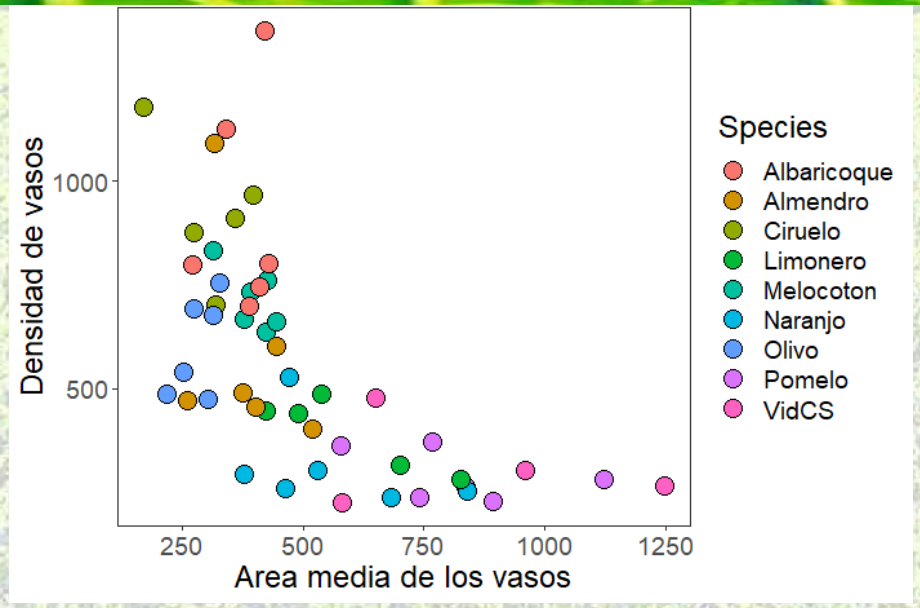


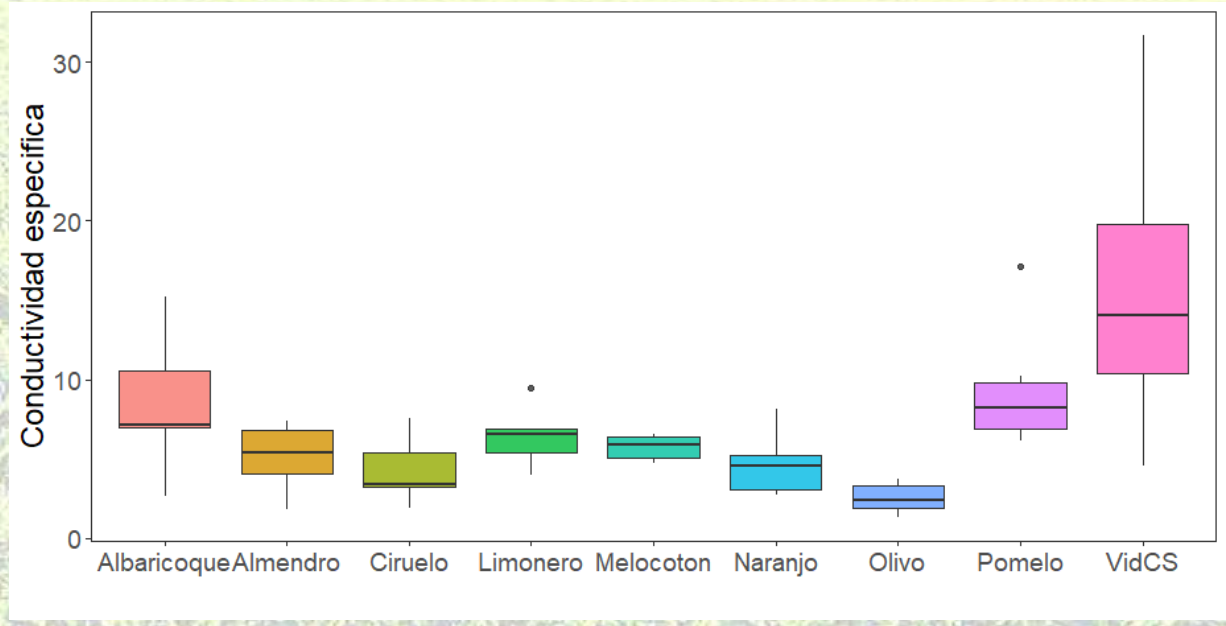


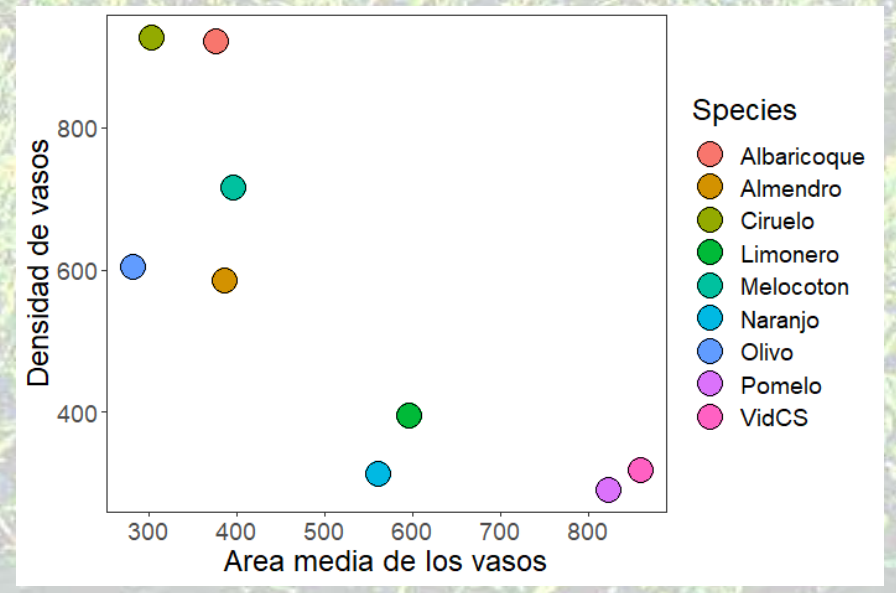
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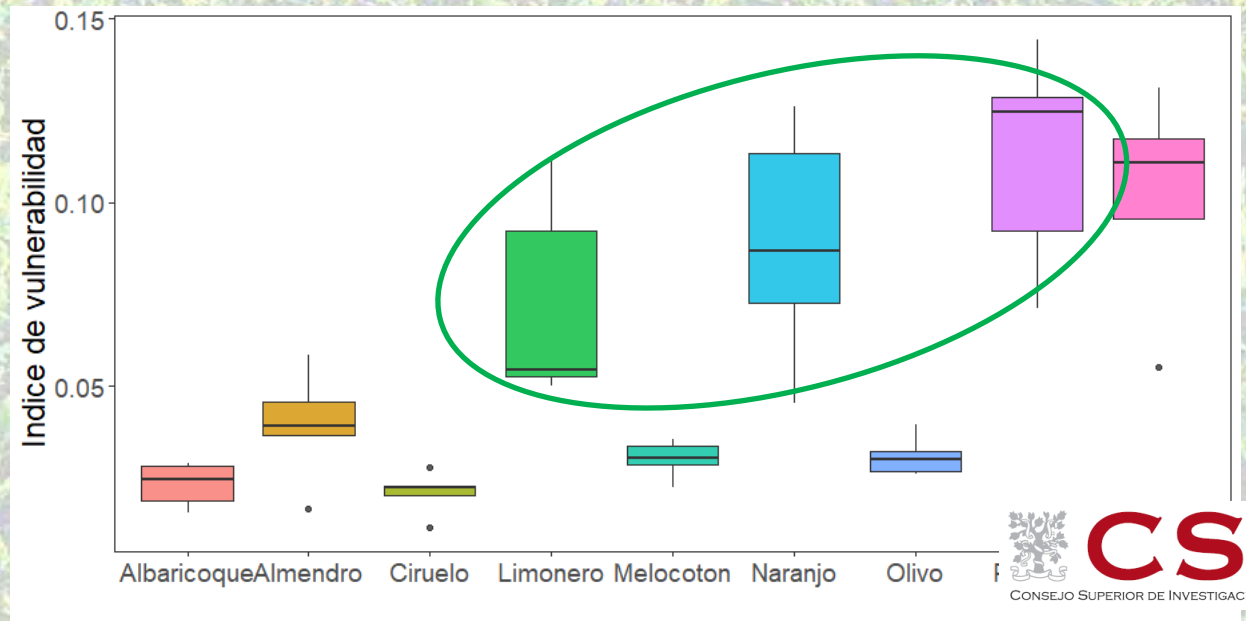
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Physiological traits





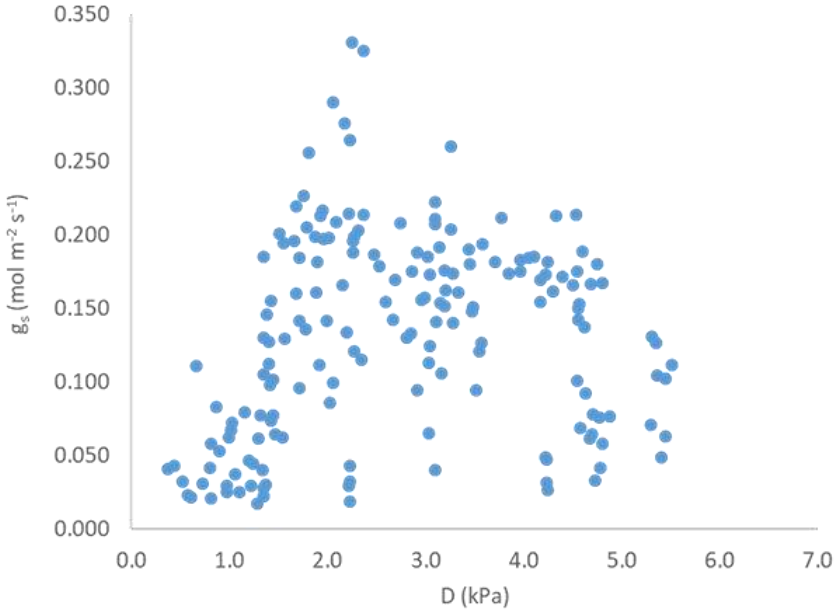




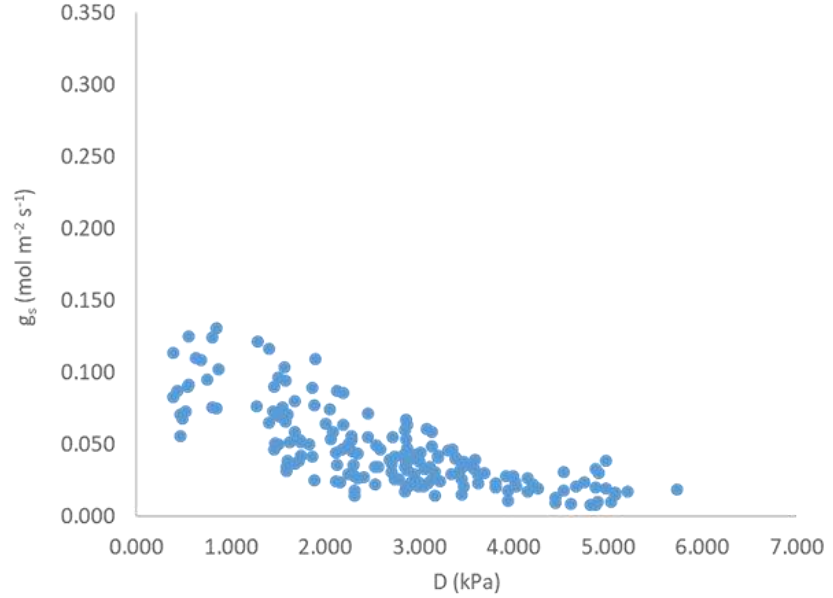
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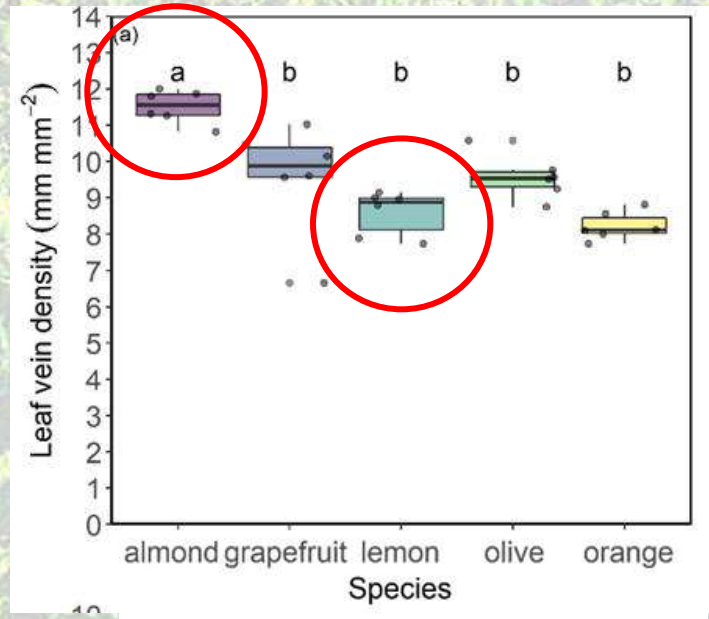
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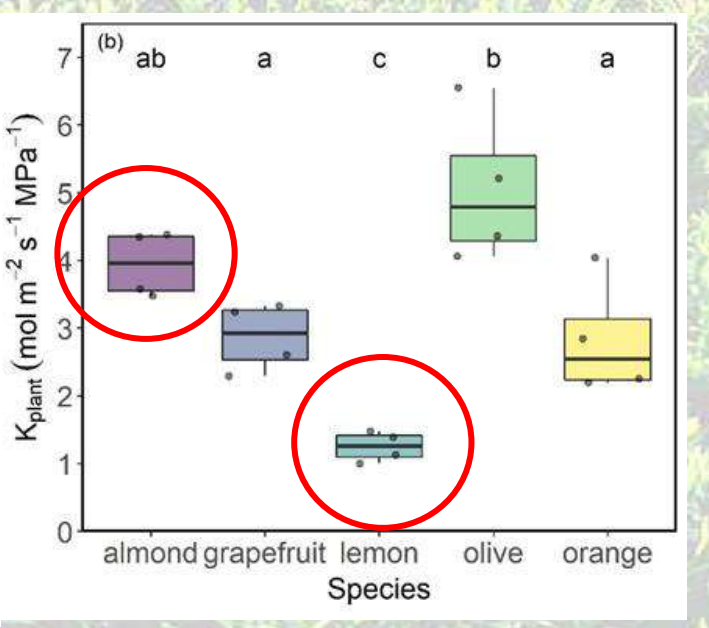
Almendro



Limonero

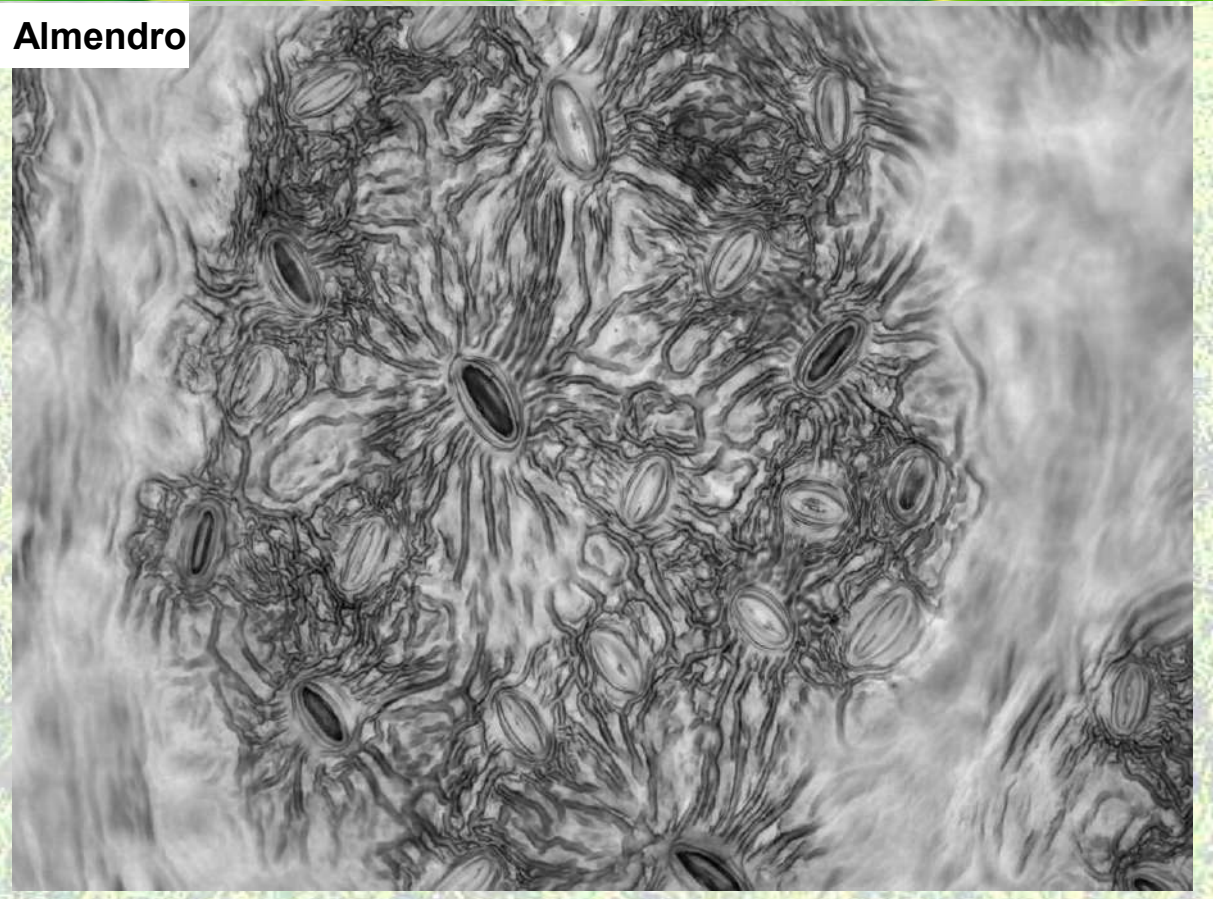




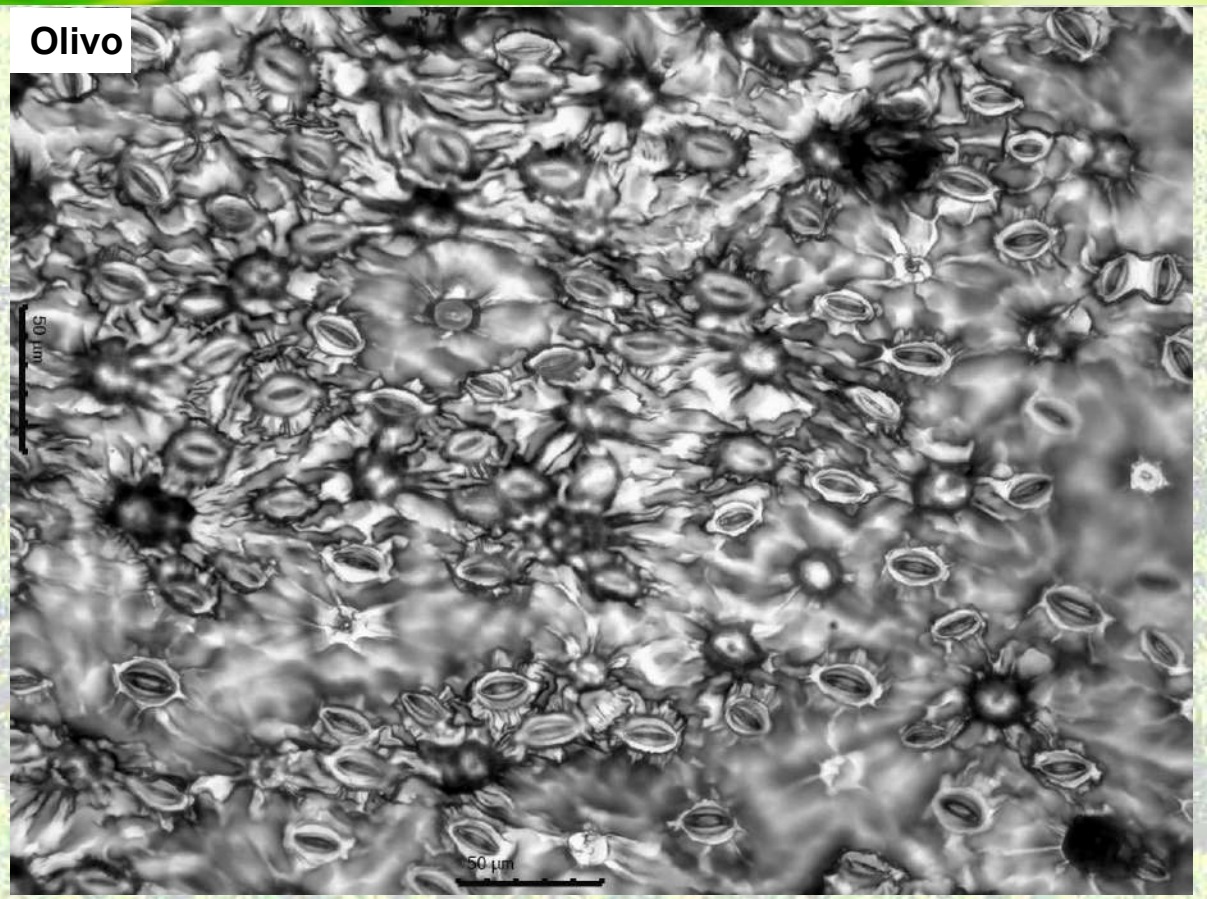


Stomata

Almendro



Olivo

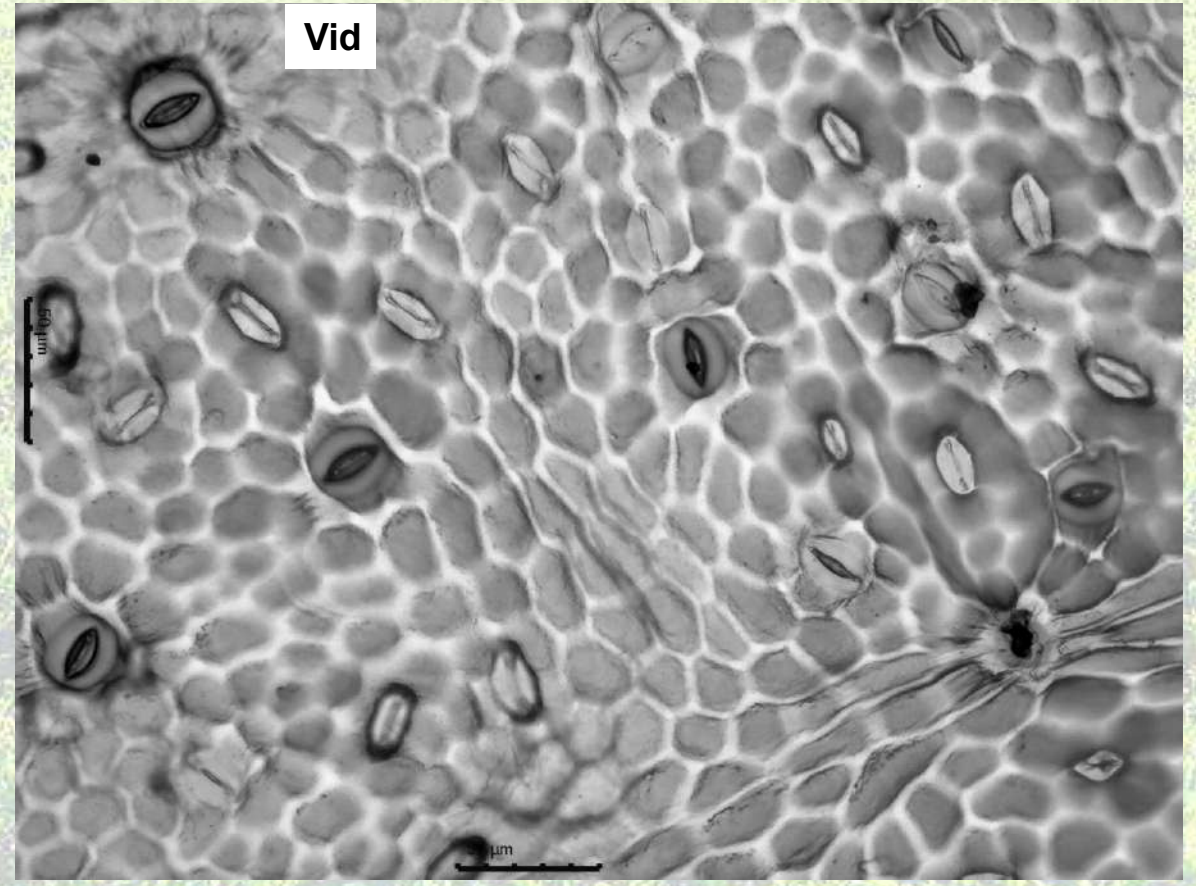


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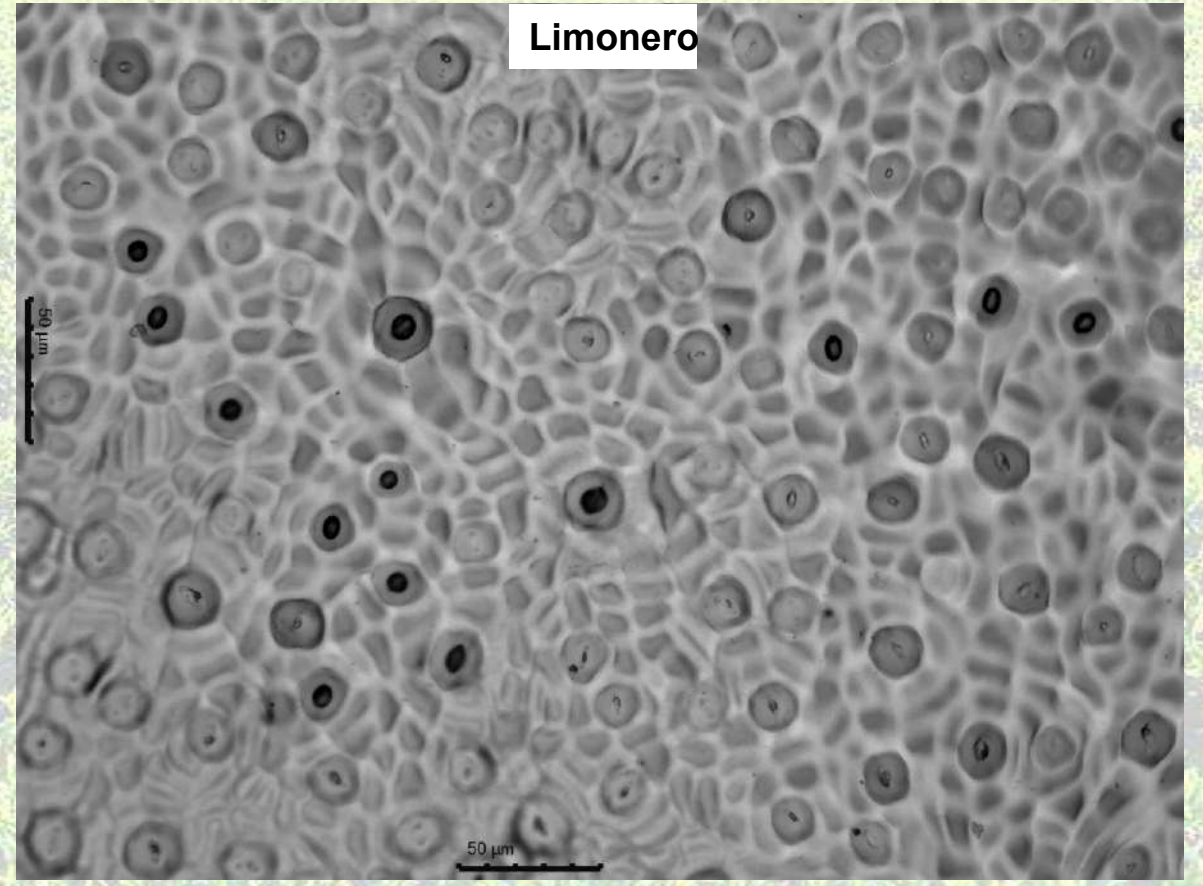
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Stomata

Vid



Limonero

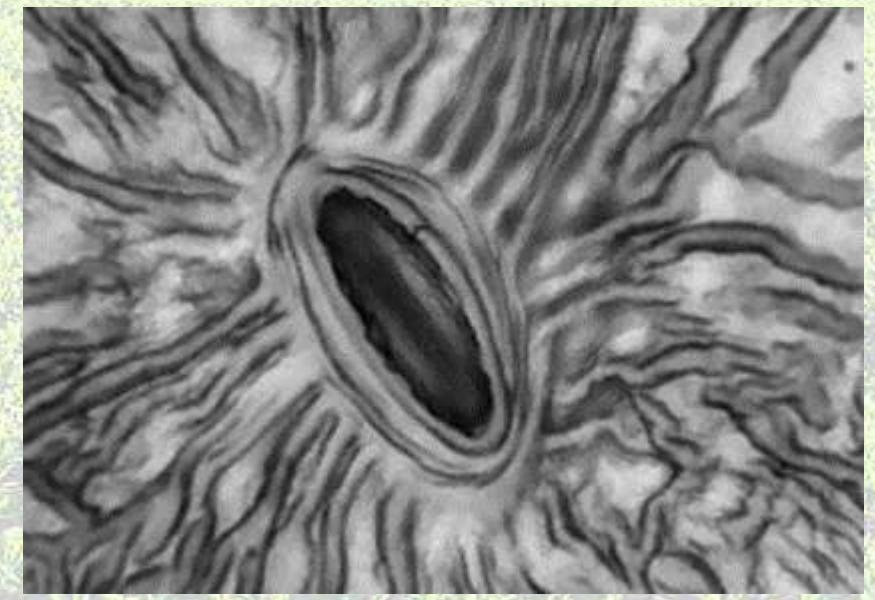


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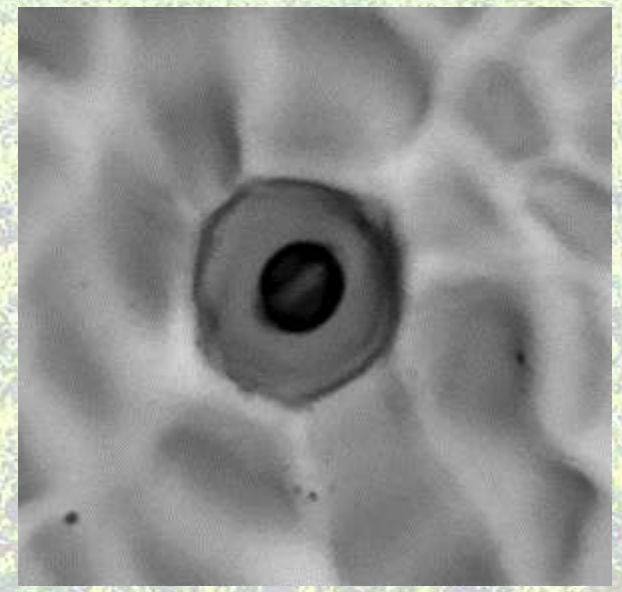
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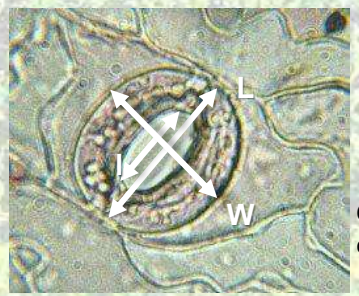
Stomata

Almond



Lemon



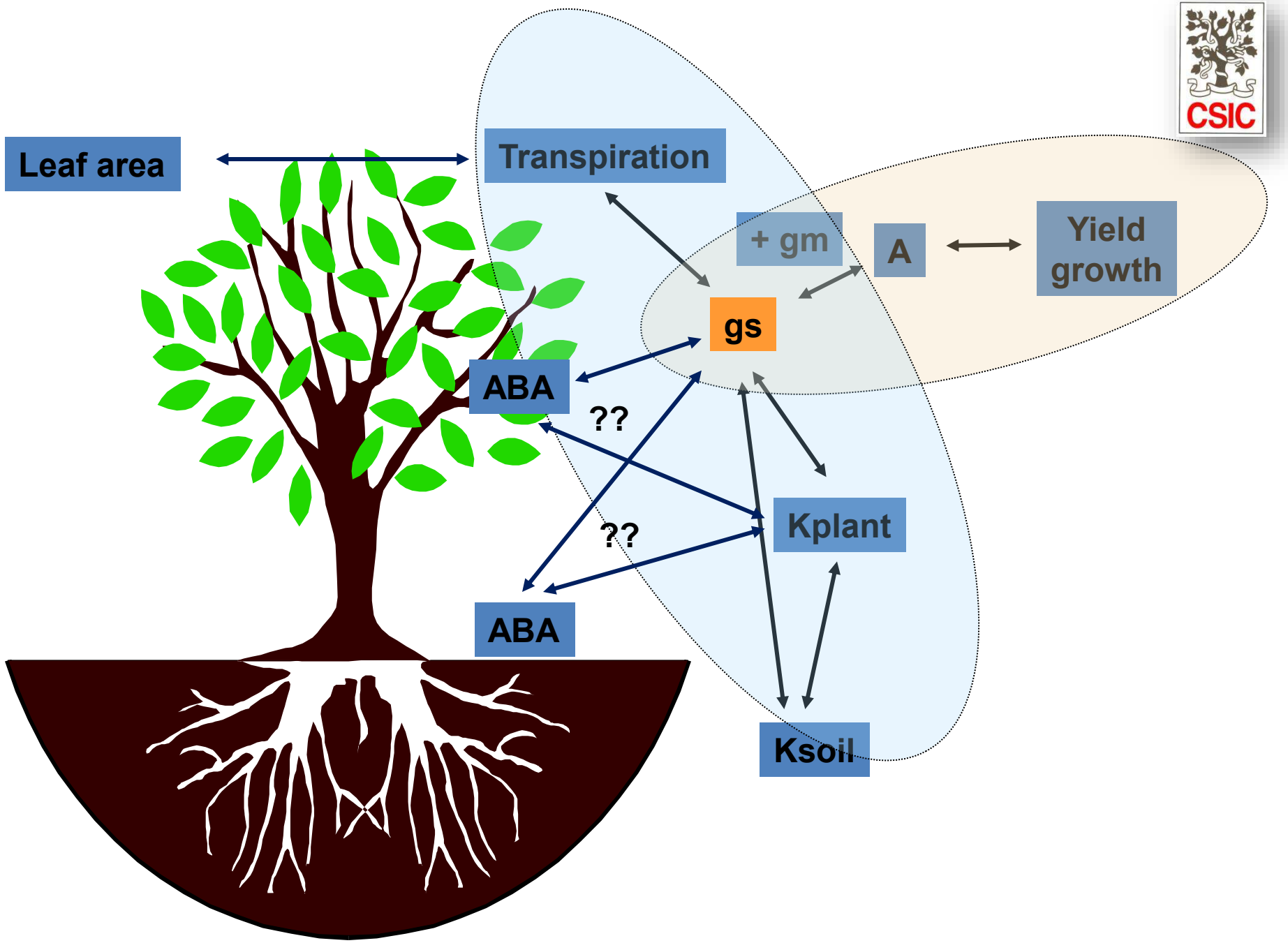


Cálculo de gs máxima teórica basada en paper de Franks et al. (2009) PC&E

Tratamiento	Stomata length (L)	Stomata width (W)	Density of stomata (D)	Stomata pore length (l)		a_{max}	S (stomata size)	a (fraction stomatal size)	$g_{w,max}$	$g_{s,max}$
	(mm)	(mm)	(número mm^{-2})	(mm)						
Almendro	28.7	15.7	202	20.1		317.31	450.59	0.704207177	**0.760**	**0.303**
Limonero	19.5	17.1	695	8.07		51.15	333.45	0.153393243	**0.574**	**0.135**

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Leaf area
Transpiration
+ gm
A
Yield growth
gs
ABA
??
??
Kplant
ABA
Ksoil
CSIC



The Ecophyisiology and Crop Irrigation (ECOVER) group

Institute for Natural Resources and Agrobiology (IRNAS)
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