DEPARTMENT OF
CIVIL AND
ENVIRONMENTAL
ENGINEERING

Laboratory lysimeter testing of irrigation strategies to reduce the food security risk

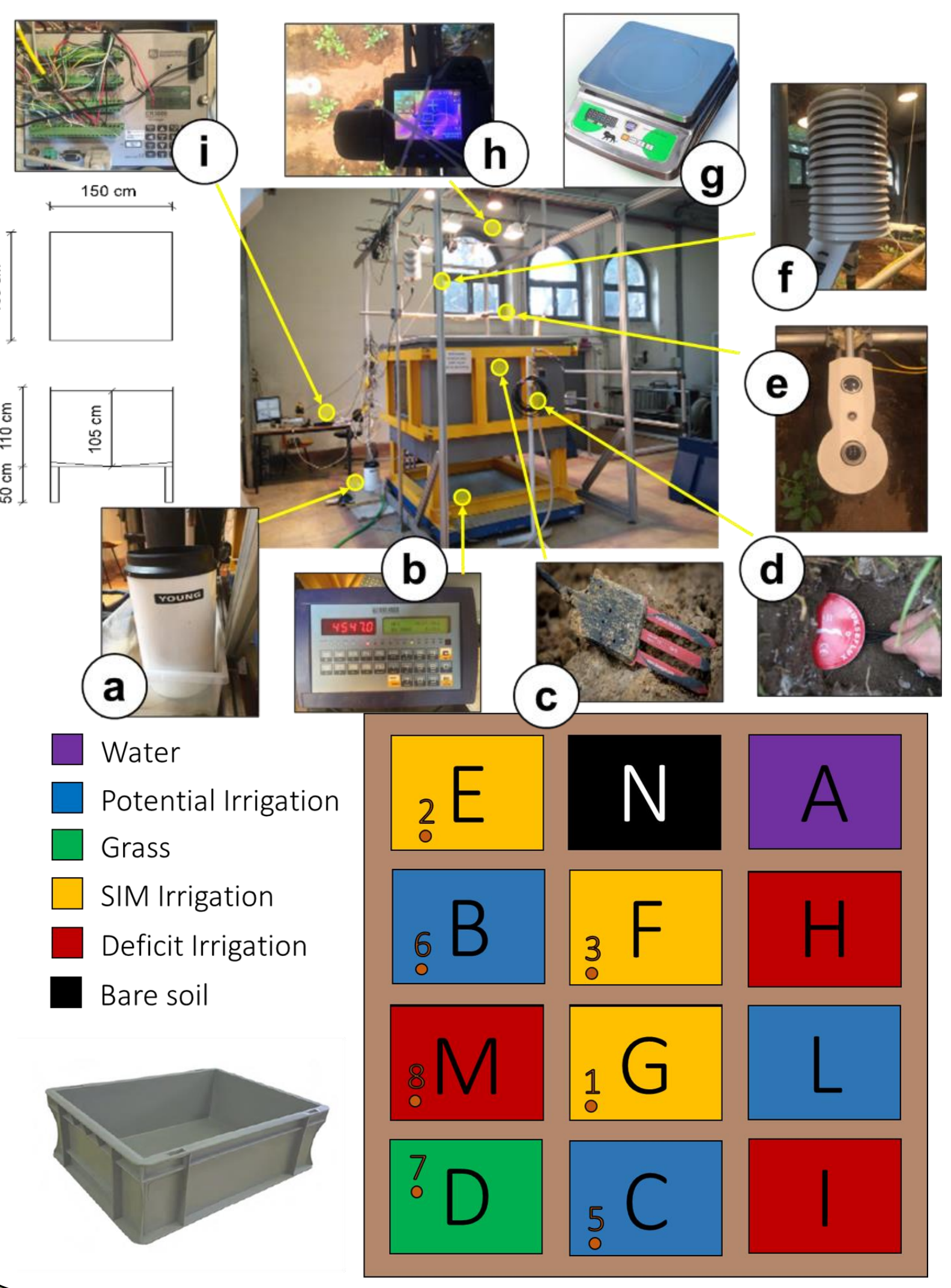
N Paciolla, C Corbari, M Mancini
Politecnico, Milano
nicola.paciolla@polimi.it

POLITECNICO
MILANO 1863

1. Introduction

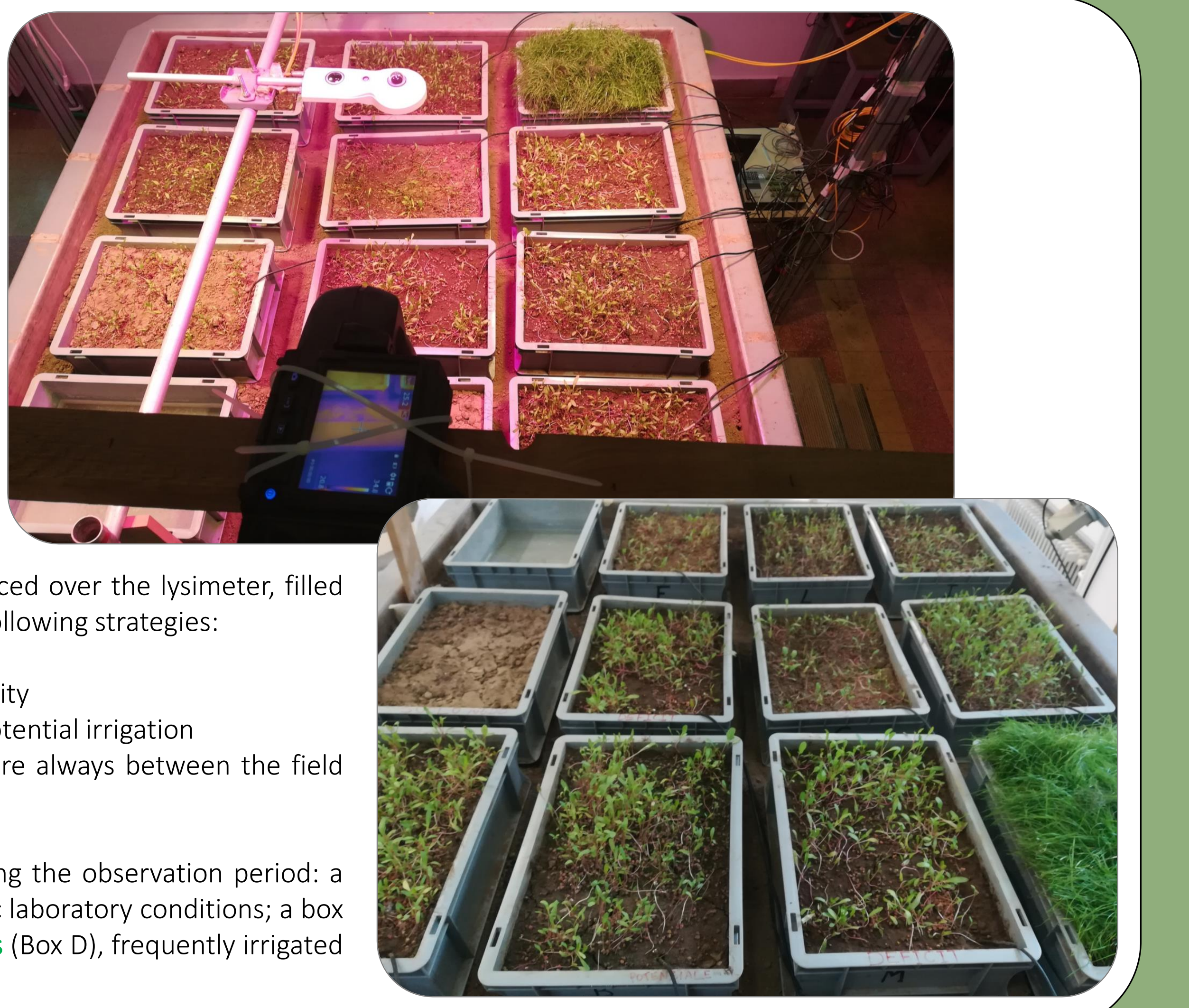
In a world that must grapple at the same time with the uncertainty of Climate Change and the challenges of a steep population growth, the importance of a sustainable agriculture is ever higher. Although only 20% of the global agricultural area is irrigated, it amounts to 40% of the world food production. Enhanced extreme-climate scenarios and food demand will determine increased water demand and water shortages for agriculture. In many water-abundant areas, farmers use all the water available, at low charges, which could be unsustainable in the years to come. In other areas, where water is scarcer, *on demand* schemes are more common, with the farmers paying for exactly the amount of water used. In these cases, a lower relative water consumption is observed. The safe conditions of a laboratory offer a framework in which different irrigation approaches can be compared, analyzing the differences in all aspects with higher accuracy than what could be done in the open field.

2. Case study



In the "Fantoli" Laboratory at Politecnico di Milano, the **lysimeter** shown on the left is a tool to monitor different water and energy fluxes that play a part in the water cycle.

- A set of four halogen lights (400 W), and one infrared and ultraviolet lamp (300 W)
- **Seven Soil Moisture (SM) probes**, usually buried at a depth of roughly 10 cm [letter c]
- A **weighing scale**, with a measurement tolerance of 2 grams (0.02 mm H_2O) [letter g]
- A **thermal camera**, bound to a wooden pole positioned at 1.2 m height above the lysimeter, retrieving both visible and thermal data [letter h]
- A **datalogger**, continuously receiving the incoming data and providing 10-minutes averages as an output [letter i]



The experimental set-up consisted in 9 **plastic boxes** (40 x 30 x 12 cm^3) placed over the lysimeter, filled with soil and sown with **lettuce**. Each box has been regulated by one of the following strategies:

- Potential irrigation aims never constraining plant activity on water availability
- Deficit irrigation aims at providing roughly half the water amount of the potential irrigation
- Optimized irrigation is a water-saving strategy that maintains soil moisture always between the field capacity and crop stress threshold. See Section 4 below for further details

Three additional boxes were placed over the lysimeter, as benchmark during the observation period: a box full of water (Box A), yielding the open-water evaporation for the specific laboratory conditions; a box full of unirrigated and unsown **soil** (Box N), left bare and dry; a box with grass (Box D), frequently irrigated to determine a laboratory equivalent of the ET_O as codified by FAO [1].

3. Experiment routine

Two experiments (**Exp.A** in late 2019 and **Exp.B** in early 2020) were designed to follow the growth of the crop under the different irrigation strategies. The day-to-day management of the experiment required the following routine:

1. every weekday, **lights were turned on at 9 and switched off at 17**;
2. around 11 a.m. each weekday, **all the boxes were weighted one by one**, determining the daily weight variation;
3. when programmed, an **overpass with the thermal camera** was performed to obtain a global temperature acquisition of the lysimeter;
4. all the boxes that required irrigation, according to their respective strategies, were **irrigated by hand**.

The weight differences allowed to compute the *a posteriori* daily ET for each pair of successive weighing instances (W) at days *d* and *d-1*:

$$W_d = W_{d-1} + Irrigation - ET - Percolation$$

$$\Delta W = W_{d-1} - W_d = (ET + Percolation) - Irrigation$$

Where Percolation can be estimated using the Brooks-Corey formulation.

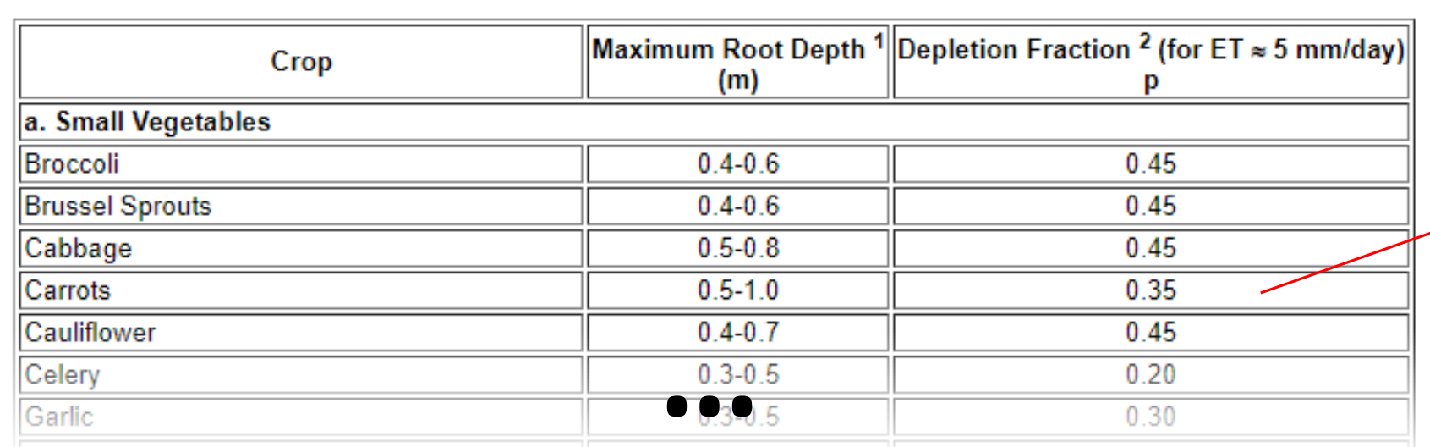
4. Irrigation strategy for risk-management

SIM irrigation prescribes that soil moisture should always be kept between two bounds:

- the **Field Capacity (FC)** identifies the limit above which the soil is not able to further retain water, which is lost by either deep percolation or surface runoff
- the **Crop Stress Threshold** (**ϑ_{crit}**), identified by FAO [1], is a lower bound below which the plant suffers water stress conditions. The value is crop- (and cultivar-) specific, and depends also on soil and climate. Water stress may result in plant development issues and consequent yield losses [2]:

$$Yield\ \%Decrease = Yield\ Response\ Factor\ \cdot ET\ \%Decrease$$

TABLE 22. Ranges of maximum effective rooting depth (Z_r), and soil water depletion fraction for no stress (p), for common crops



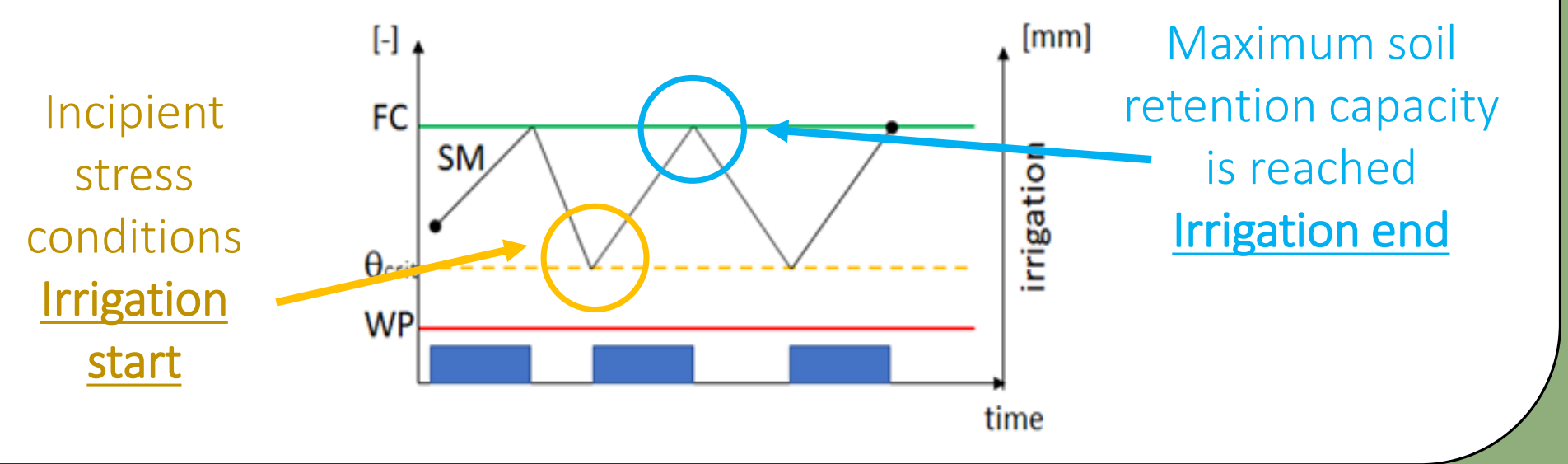
Crop	Maximum Root Depth [1] (m)	Depletion Fraction [2] (for ET ≈ 5 mm/day) p
a. Small Vegetables		
Broccoli	0.4-0.6	0.45
Brussel Sprouts	0.4-0.6	0.45
Cabbage	0.5-0.8	0.45
Carrots	0.5-1.0	0.35
Cauliflower	0.4-0.7	0.45
Celery	0.3-0.5	0.20
Garlic	0.3-0.5	0.30

$$p = p_{FAO-table} + 0.04(5 - ET_c)$$

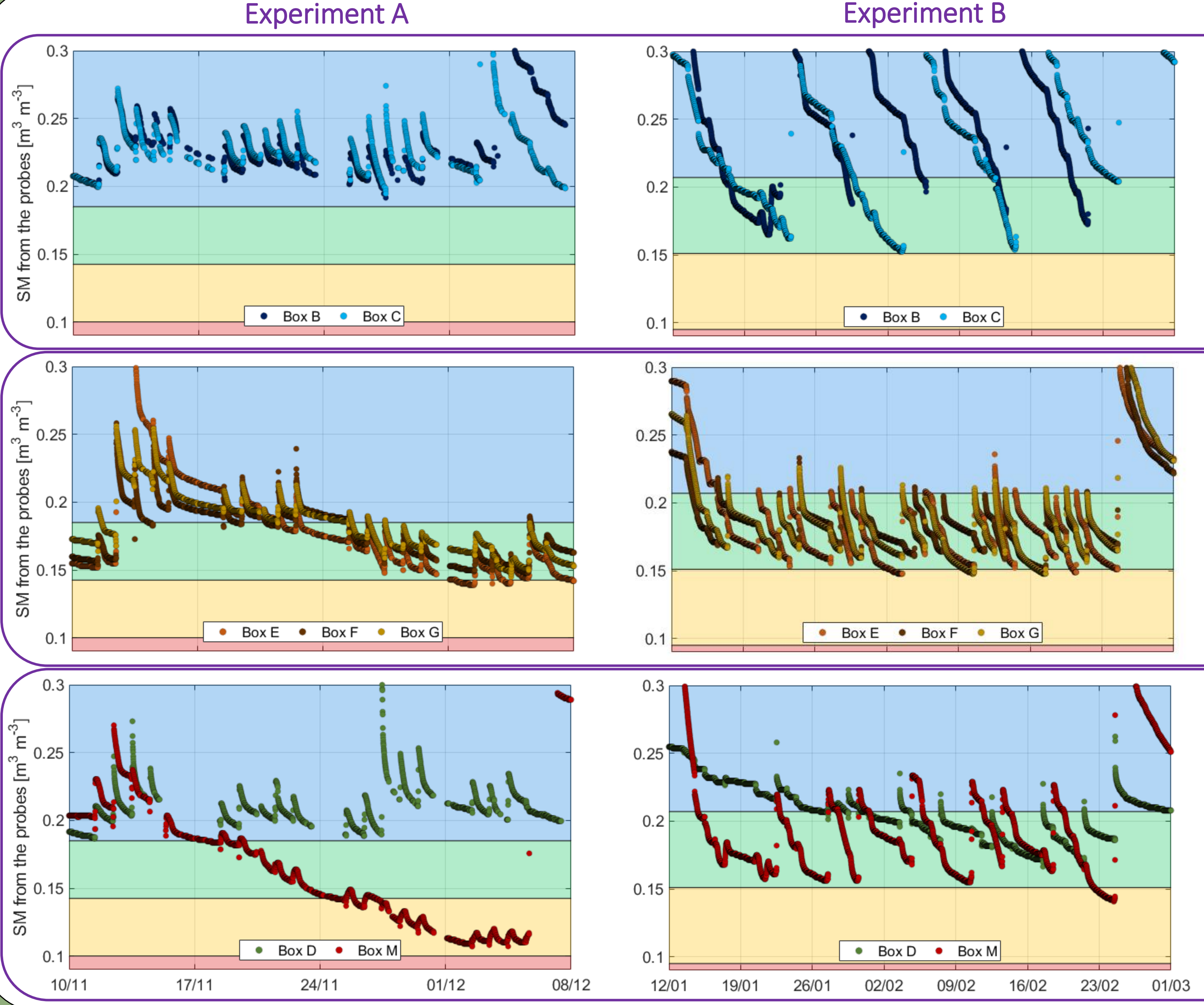
$$\vartheta_{crit} = FC - p(FC - WP)$$

If a continuous knowledge (or modelling) of Soil Moisture is available, and pending on-demand water availability, it is possible to irrigate only when necessary and with exactly the right amount, avoiding stressful situations and preserving the water resource for future employment.

As **water availability** is **increasingly lower** and **extreme events** (such as **droughts** or **heat waves**) are becoming more and more frequent, the possibility of saving some water to cope with such events (preventing water- and heat-stress conditions of plant) is key to maintain acceptable crop yields that ensure **food security**.

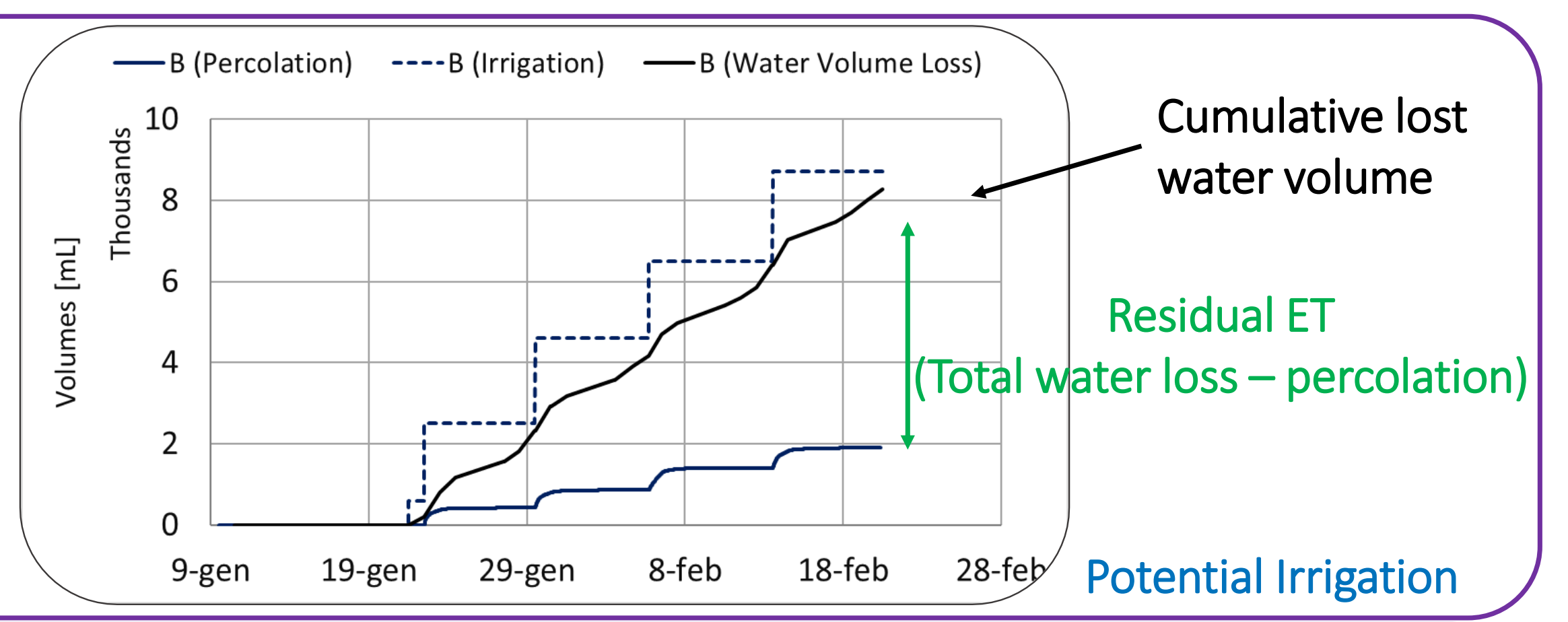


5. SM time series and water volumes



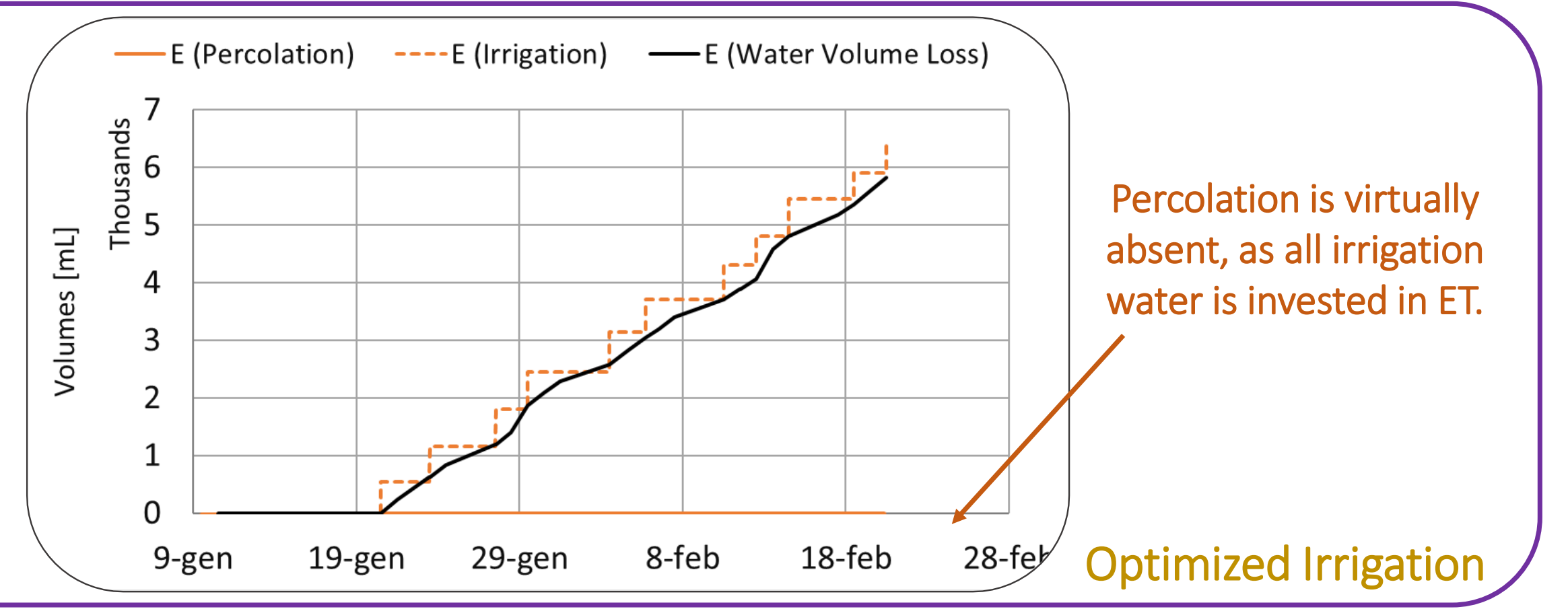
Potential irrigation

- In Experiment A, high SM values were continuously maintained throughout the period
- In Experiment B, a more cyclical approach was chosen, allowing the soil to dry up to the crop water stress threshold before almost saturating it
- The cumulated Percolation is shown to increase right after each irrigation event, before virtually ceasing as Soil Moisture gets lower
- ET increases with the vegetation growth



Optimized irrigation

- SM is "constrained" between Field Capacity and Crop Stress thresholds. SM falls below CST only when it is impossible to irrigate at that specific moment (e.g., weekends, night-time).
- The amount of irrigation required to reach FC is calibrated to each sensor after some testing.
- A continuous soil moisture monitoring is necessary, in order to avoid any crop-stress conditions and provide the right amount of water to the plant.

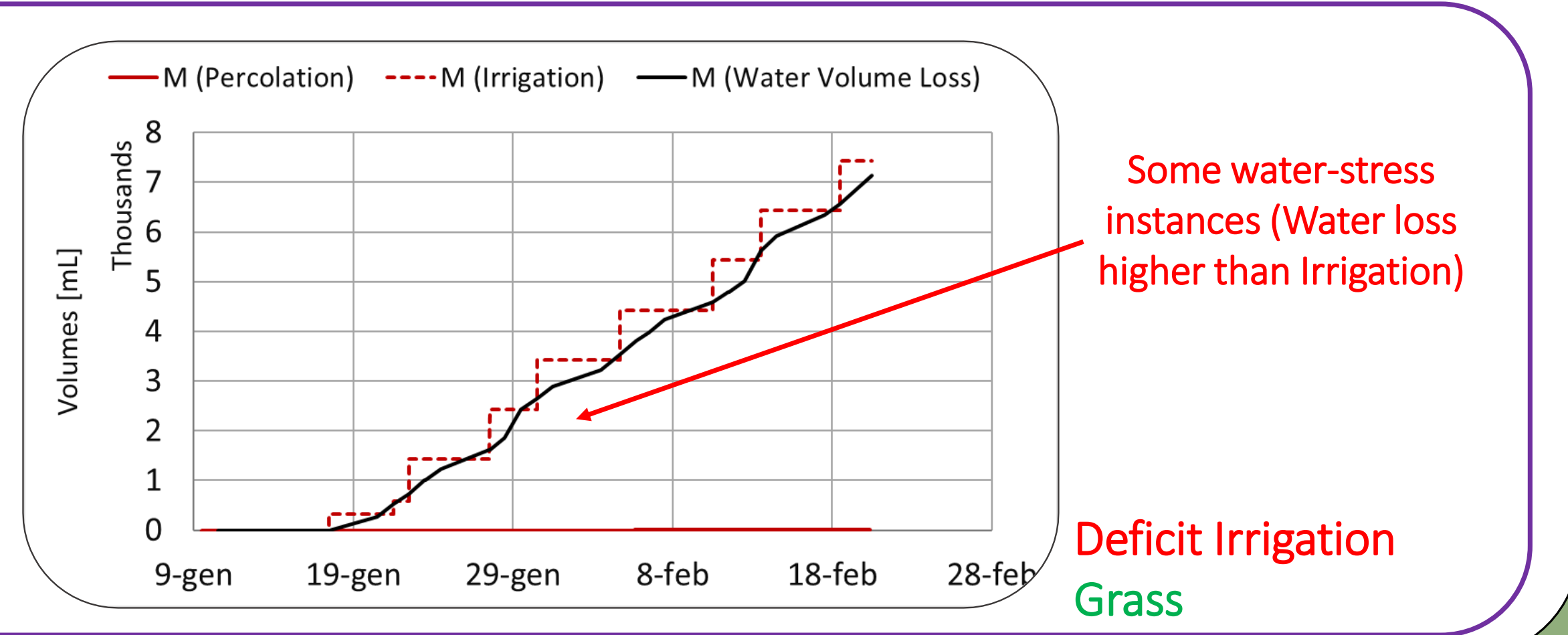


Deficit irrigation

- In Experiment A, it was provided half of the water that was being given to the Potential-irrigation
- In Experiment B, it was provided a given amount any time the boxes reached the crop stress threshold

Grass box

- In Experiment A, it was irrigated almost daily, staying always well above field capacity
- In Experiment B, the actual water presence in the soil was slightly underestimated by the SM probe measurements

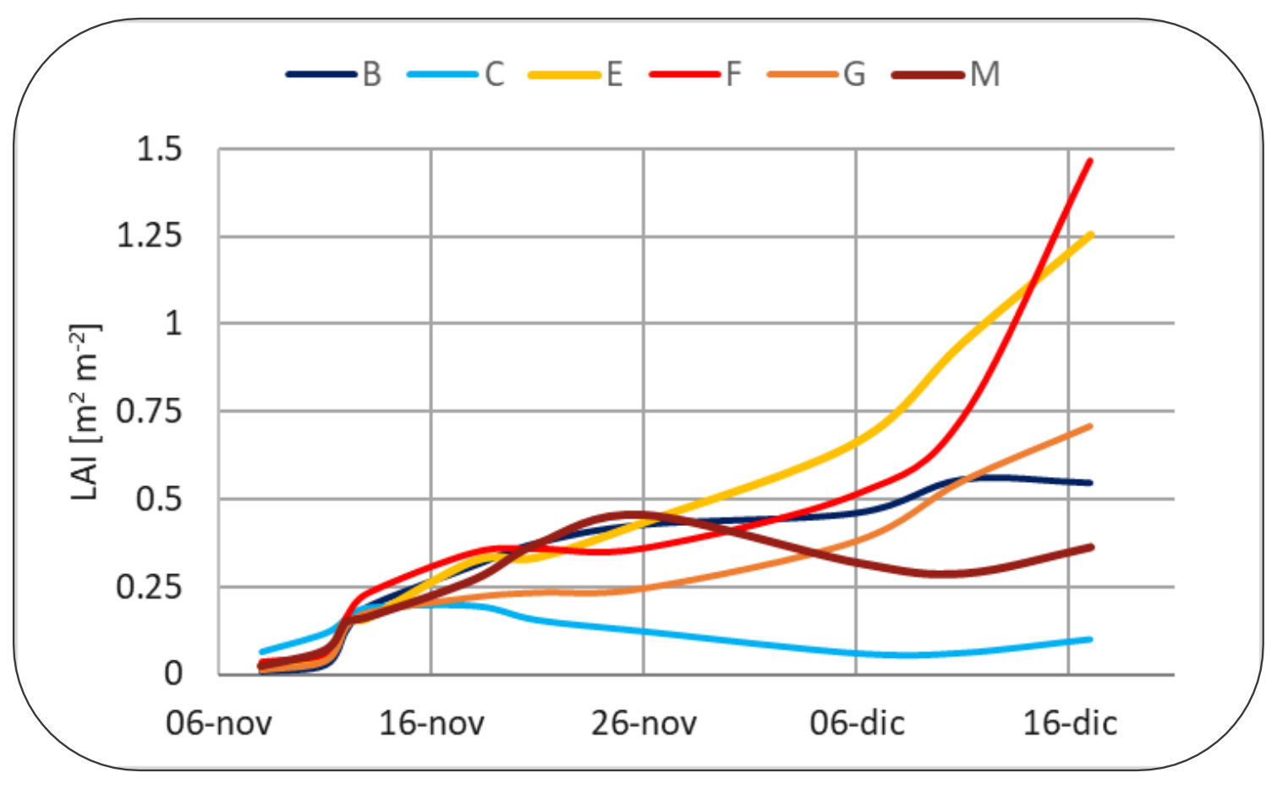


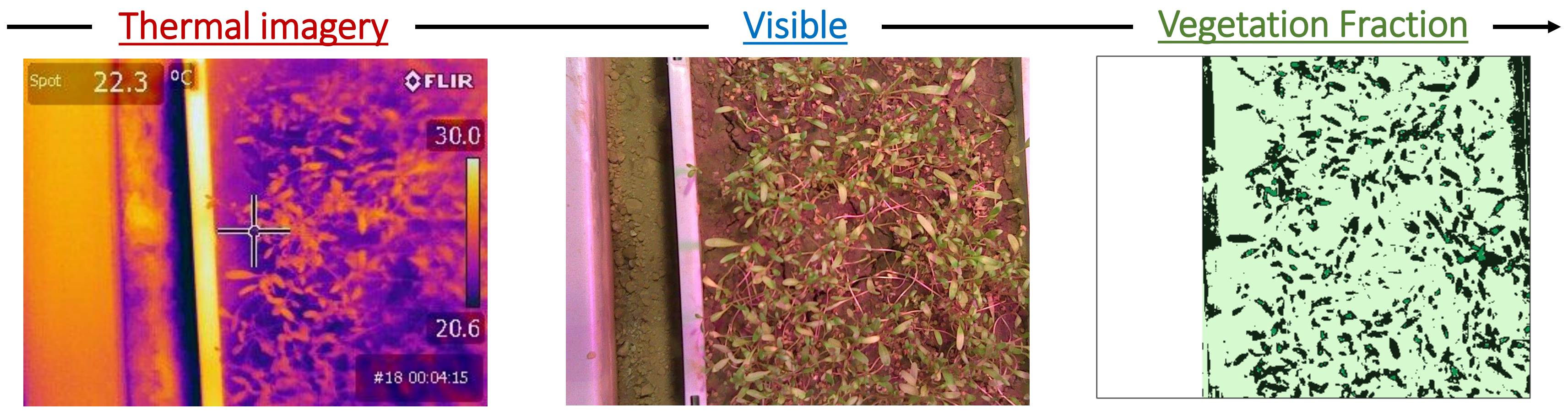
6. Thermal observations and LAI

The thermal camera overpasses provides high-resolution data at 0.5 cm. The leaves appear warmer than the soil which has just been irrigated. From each image, the number of vegetated pixels yields the Vegetation Fraction (f_V) of the single box. From it, it is possible to compute the Leaf Area Index (LAI), known as the amount of leaf area per square meter (m^2 m^{-2}), from the following formulation:

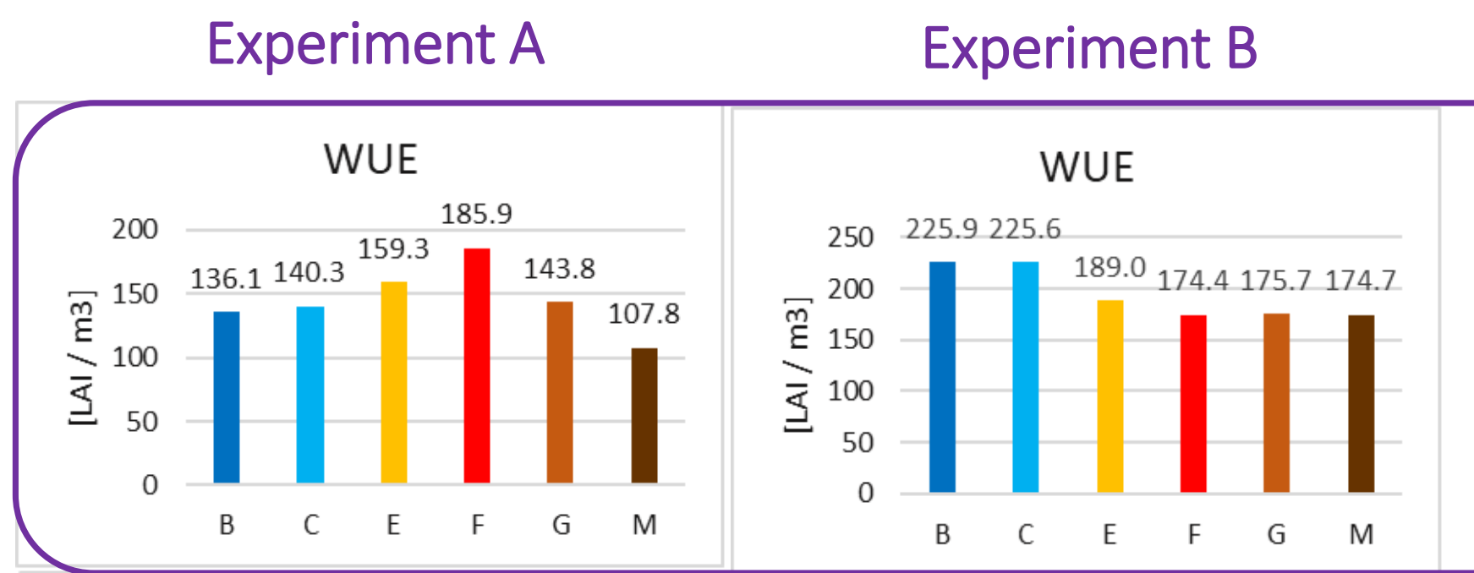
$$LAI = \frac{-\ln(1 - f_V)}{0.5}$$

In the following Section 7, LAI has been used as a proxy for crop yield (as it was not possible to measure the final yield), provided the intrinsic link between the two. On the right, an example of **Leaf Area Index growth** for all boxes during Exp.A.



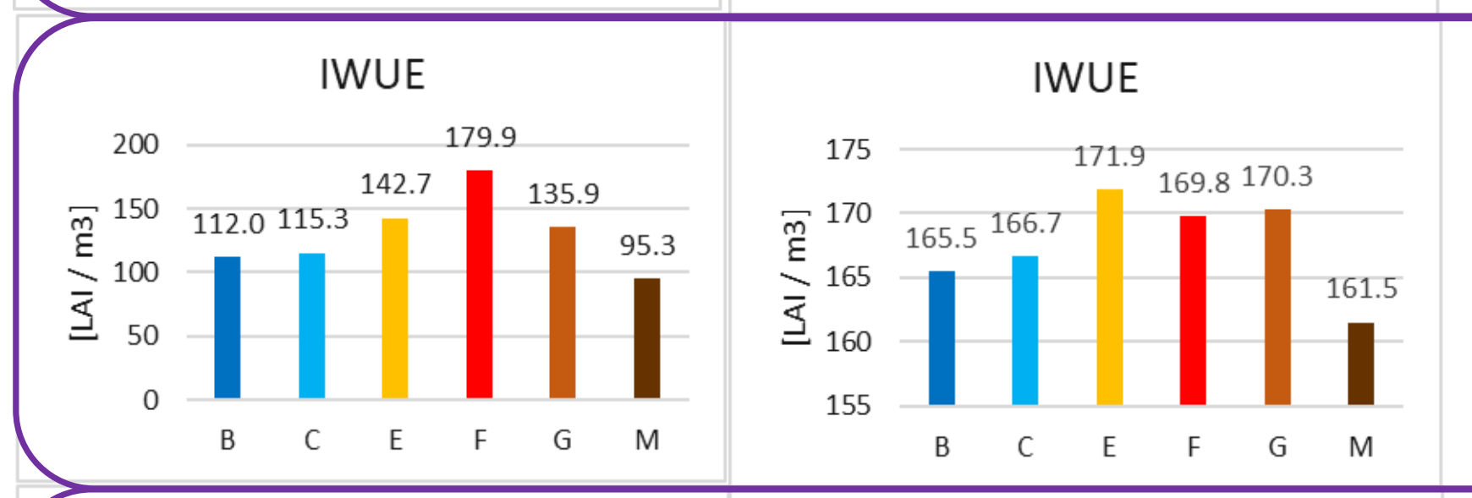


7. Water management and crop productivity Indicators



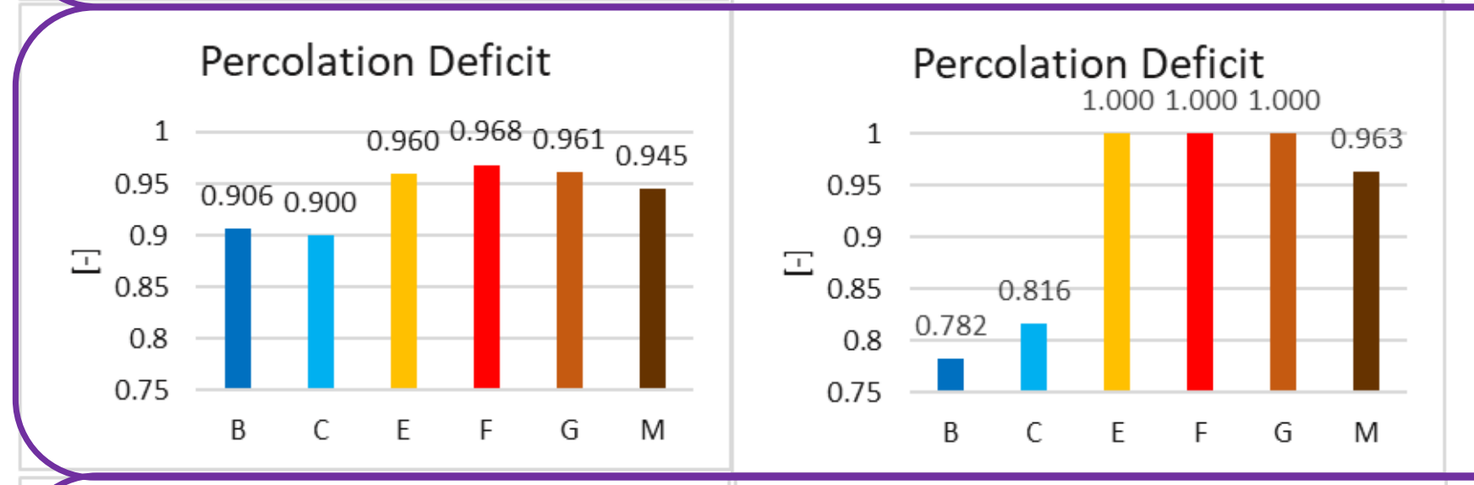
The **Water Use Efficiency** (**WUE**) relates the crop production obtained per unit volume of evapo-transpired water, an indirect estimate of plant activity.

$$WUE = \frac{Crop\ yield}{Evapotranspiration}$$



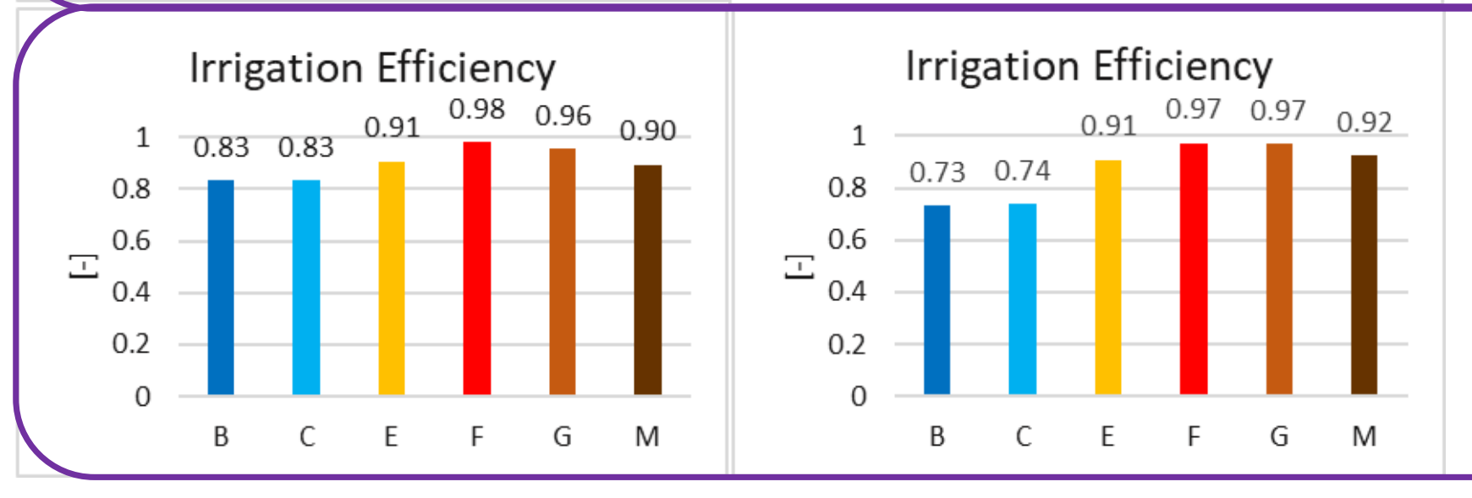
The **Irrigation Water Use Efficiency** (**IWUE**) identifies the crop production per unit volume of water used in irrigation.

$$IWUE = \frac{Crop\ yield}{Irrigation}$$



The **Percolation Deficit** (**PD**) relates the amount of water available to the plant, once percolation has been taken into account.

$$PD = \frac{Irrigation - Percolation}{Irrigation}$$



The **Irrigation Efficiency** (**IE**) compares Evapotranspiration and Irrigation, relating plant activity to artificial water inputs.

$$IE = \frac{Evapotranspiration}{Irrigation}$$

6. Discussion

Potential Irrigation showed similar crop yields notwithstanding the considerable amounts of irrigation water employed. Deficit Irrigation showed good levels of water usage, but experienced some water stress and underperformed, in terms of final crop yield. The Optimized Irrigation, although requiring a more consistent monitoring, provided positive final crop yields with virtually no percolation and low amounts of irrigation water. It allows the farmer to be more prepared to crop failure risk, avoiding crop water stress and reduce the effects of climatic extreme events.

Conclusions

(1) Potential Irrigation overestimates the actual amount of water necessary to the plant for its development. (2) Deficit Irrigation, although saving a considerable fraction of the water resource, can harm the plant increasing the risk of inducing water-stress-related hampering of the final crop yield. (3) Optimized Irrigation allows to provide the plant with the exact amount of required water, avoiding water stress and water losses to the environment. The saved water allows to be prepared against extreme weather events (droughts, heat waves), reducing the risk of crop failure

References & Acknowledgements

[1] Allen, RG, Pereira, LS, Raes, D, Smith, M (1998) "Crop evapotranspiration: guidelines for computing crop water requirements", FAO Irrigation and Drainage Paper No. 56, Rome, Italy
[2] Steduto, P, Hsiao, TC, Fereres, E, Raes, D (2012) "Crop yield response to water", FAO Irrigation and Drainage Paper No. 66, Rome, Italy

This work has been performed under the framework of the SMARTIES (2019-2023) project (PRIMA, Horizon 2020)