# Monitoring System in an Agrivoltaic Greenhouse in Southern Spain

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# Outline

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1. Motivation: Greenhouses in Almería, Spain
2. Agrivoltaic greenhouse experiment
    1. Planning
    2. Microclimate monitoring system
3. Irradiance monitoring
    1. Irradiance distribution
    2. Radiation levels close to side walls
    3. Comparison simulation – experiment
4. Plant physiology and crop yield
    1. Tomato cycle photos
    2. Daily GHI and number of leaves
    3. Fresh weight, number of fruits and sugar content
5. Summary

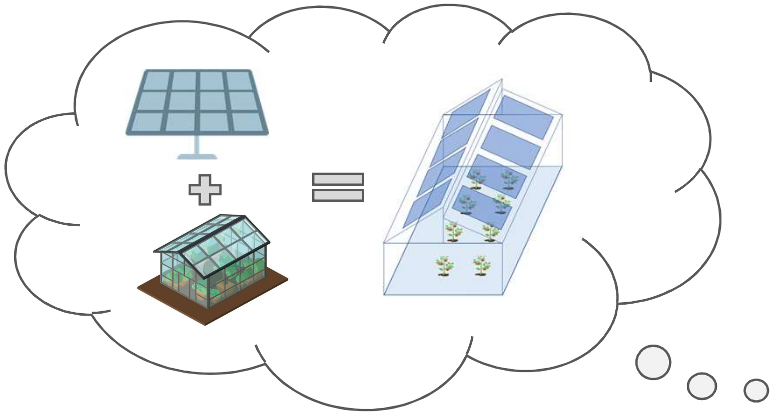
# Motivation: Greenhouses in Almería, Spain

view over Spain from the ISS, source: ESA.int

- the *Mar de Plastico* (Sea of Plastic): a 33,000 hectares network of greenhouses

- approx. 3000 sun hours per year [1]

→ greenhouse cultivation possible everyday of the year



- local high irradiation levels combined with existing infrastructure provide great potential for agrivoltaic solutions
- theoretical maximum PV coverage of about 44% for East-West oriented greenhouses [2]
- agrivoltaic concepts can actively support light management of growers

Development of an overall agrivoltaic greenhouse model by DLR and validation with agrivoltaic greenhouse experiment

[1] AEMET (Agencia Estatal De Meteorologia, Gobierno de España). Valores Climatológicos Normales.
[2] Hanrieder, N. et al. **"Estimation of maximum photovoltaic cover ratios in greenhouses based on global irradiance data",** Applied Energy (2024).

# Outline

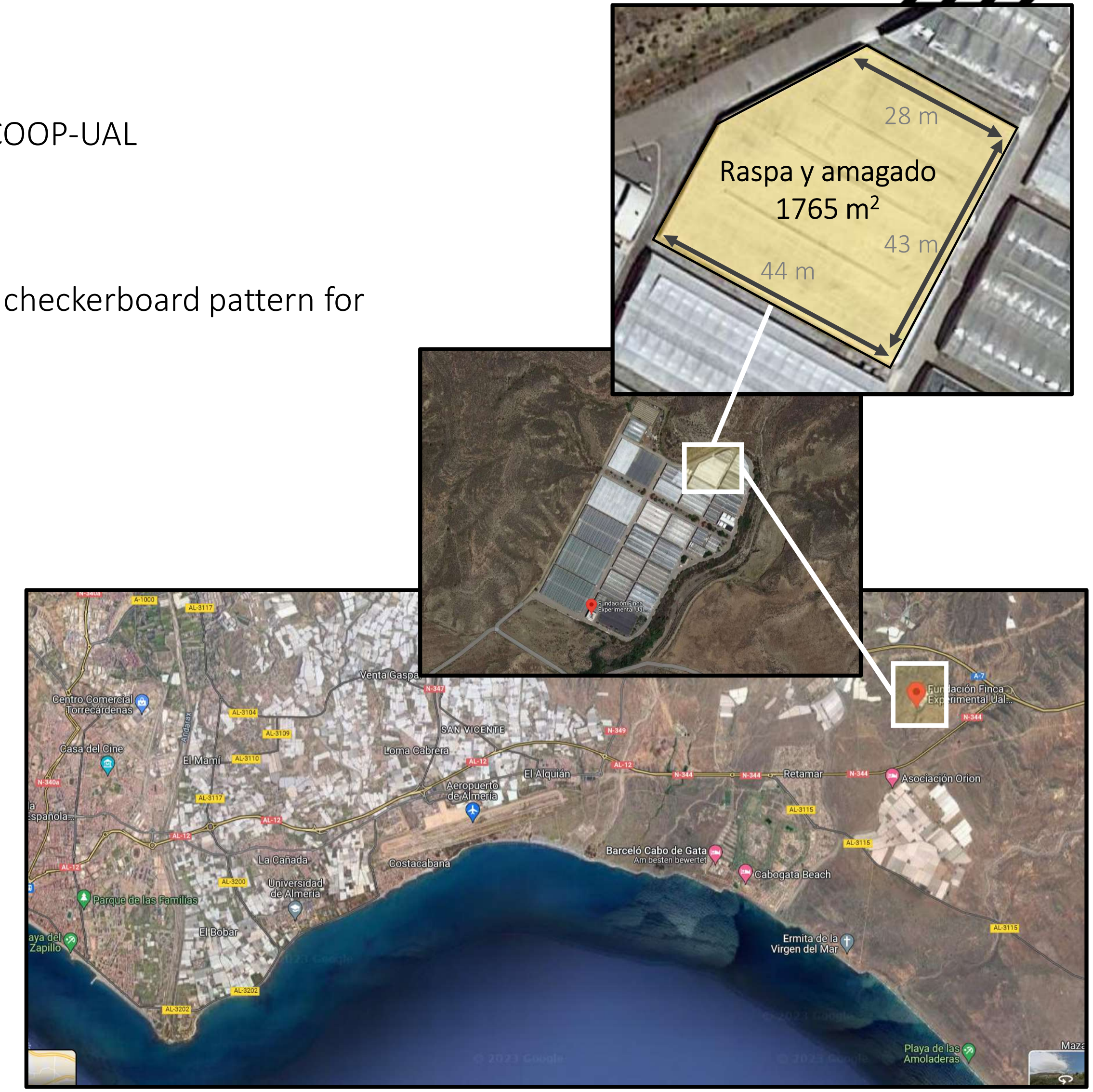
# Agrivoltaic greenhouse experiment

<u>Planning:</u>

- Collaboration with company ANECOOP and Fundación ANECOOP-UAL
- August 2023: access to GH for monitoring system installation

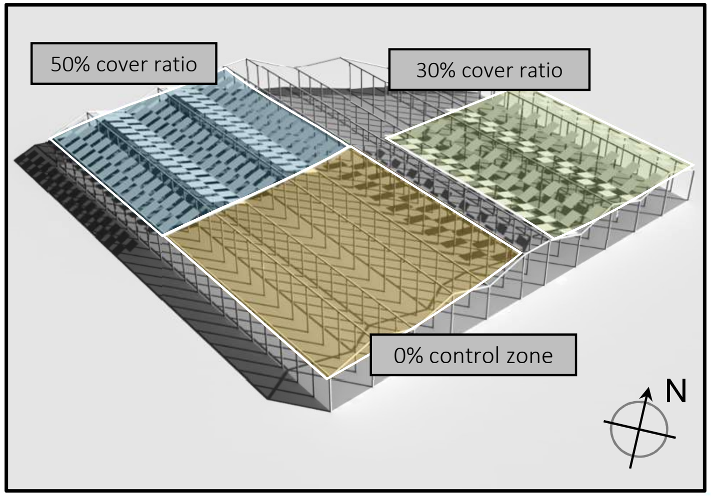
State of the art (2023):

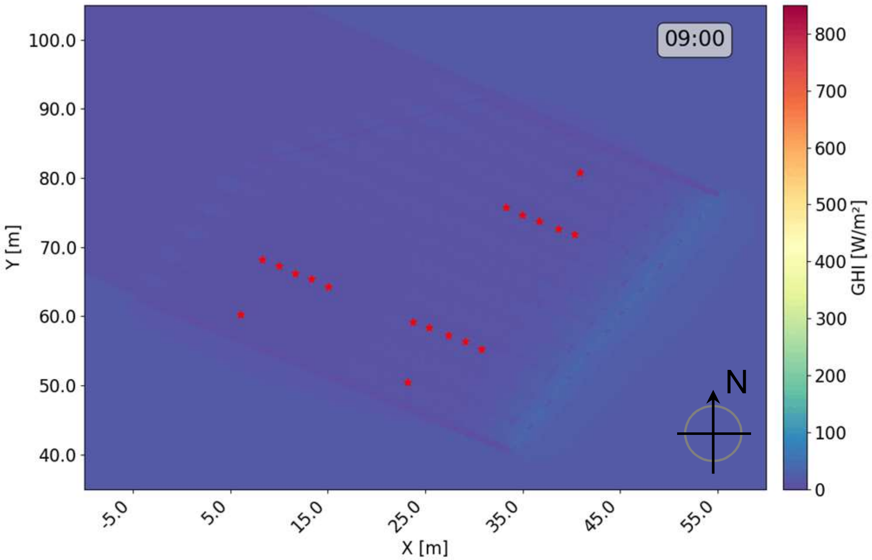
- lack on shading studies with higher shading ratios (>30%) in checkerboard pattern for raspa y amagado greenhouses



# Agrivoltaic greenhouse experiment

**Planning:**



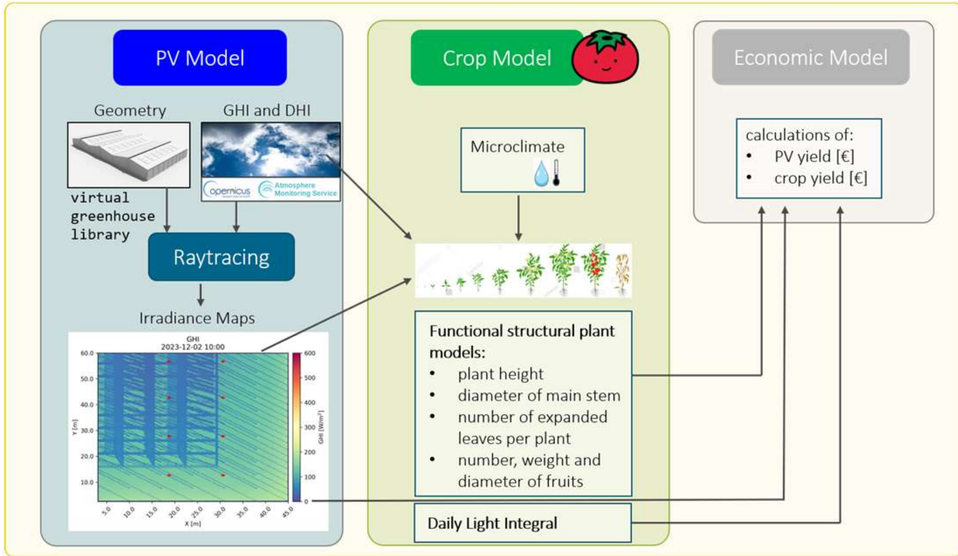




Usage of **DLR agrivoltaic greenhouse model** to define experiment:

- virtual copy of GH implemented to define experimental layout

→ **definition of two test zones with 30% and 50% PV cover ratio and one 0% control zone** (module size 1m x 1.7m)

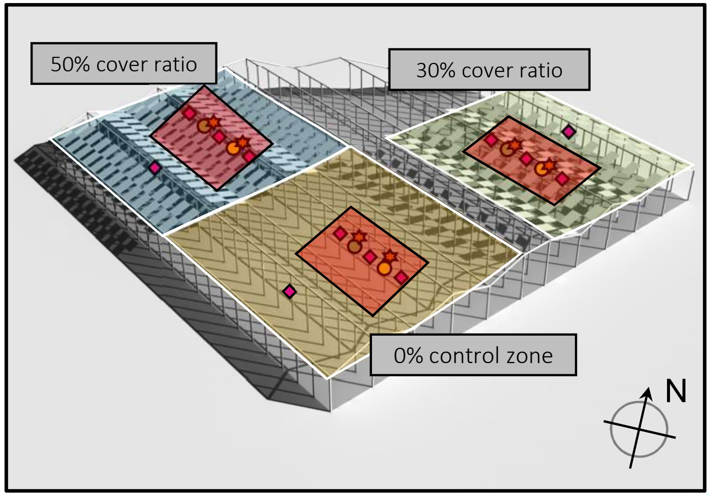
DLR's ray tracing based agrivoltaic model [3]

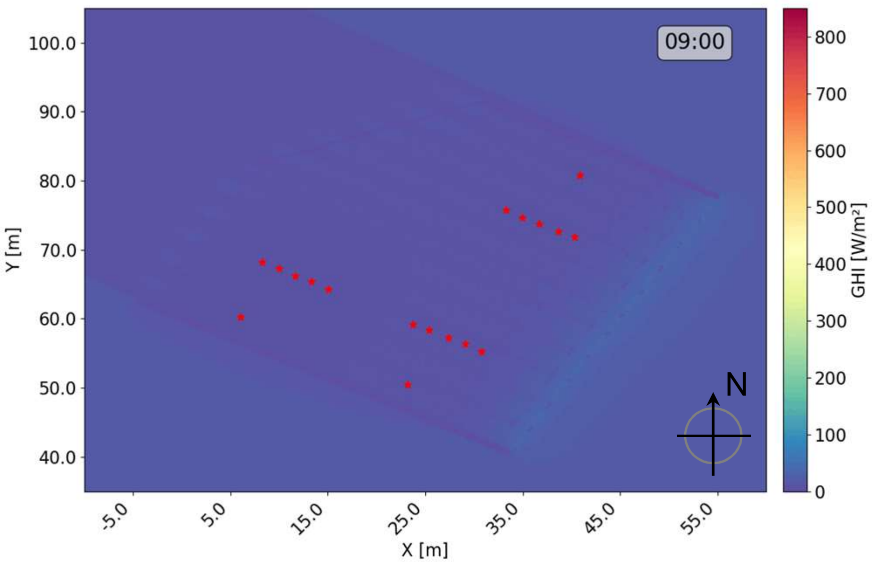



[3] Kujawa, A. et al. "**Modeling of bifacial AgriPV greenhouses in southern Spain**", EUPVSEC conference (Lisbon, 2023).

# Agrivoltaic greenhouse experiment

Microclimate monitoring system:



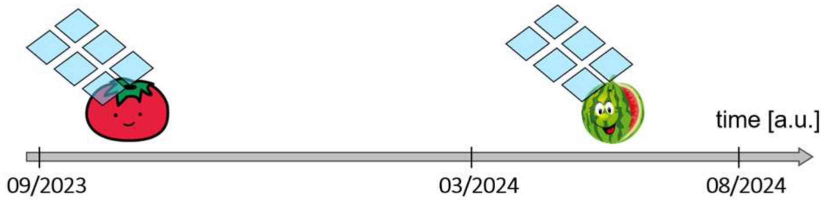




## Microclimate Monitoring System

Continuous data monitoring with one-minute temporal resolution

in each zone:

- 4 pyranometers (3 in center, 1 at the edge towards side wall)
- 1 UV-A sensor
- 1 UV–B sensor
- 2 temperature and relative humidity sensors




20 representative plants were monitored

- plant physiology
- crop yield

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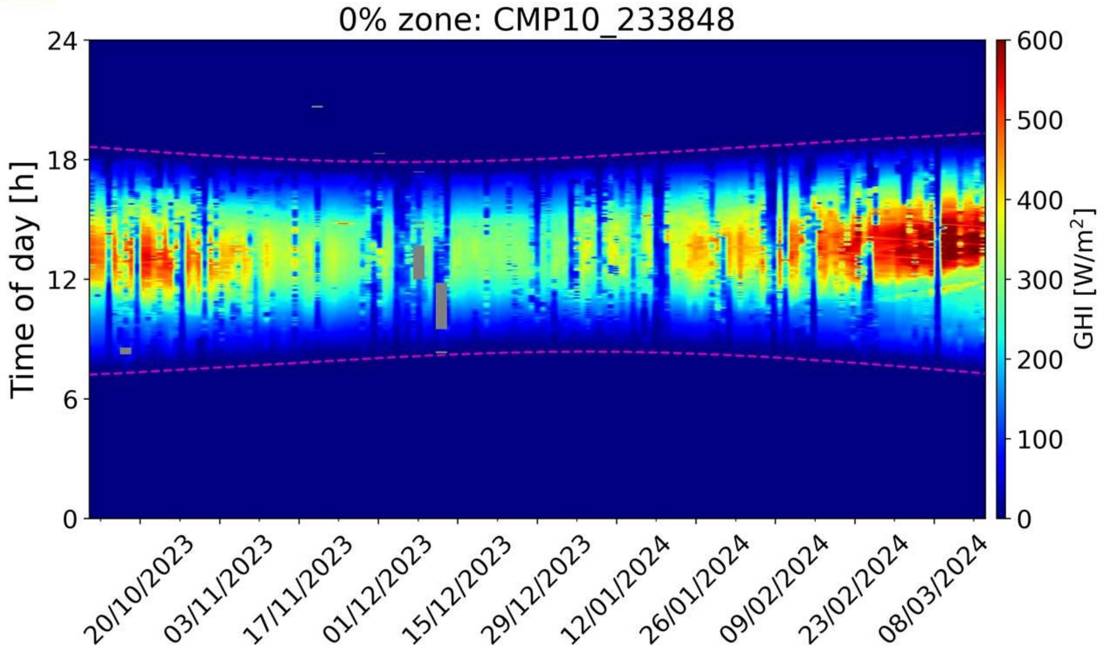
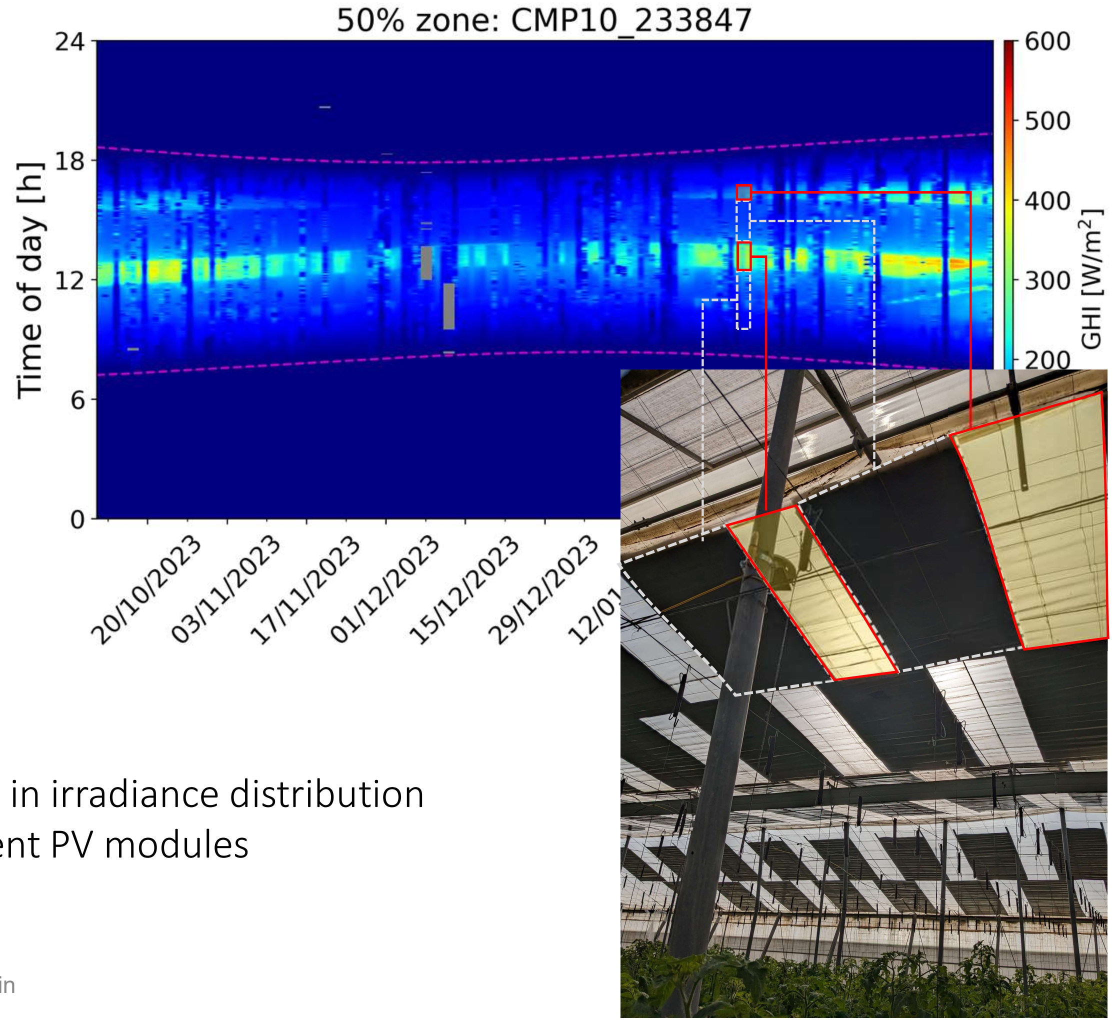
# Irradiance monitoring

Irradiance distribution:



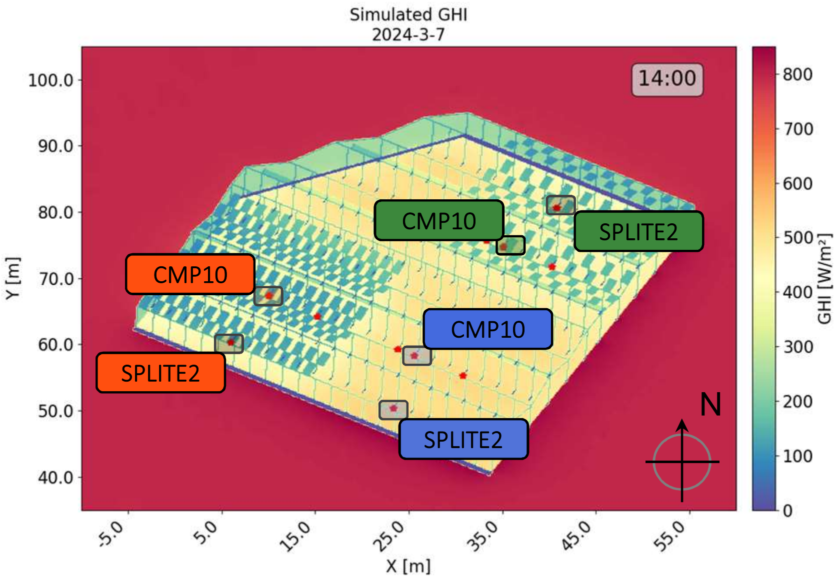



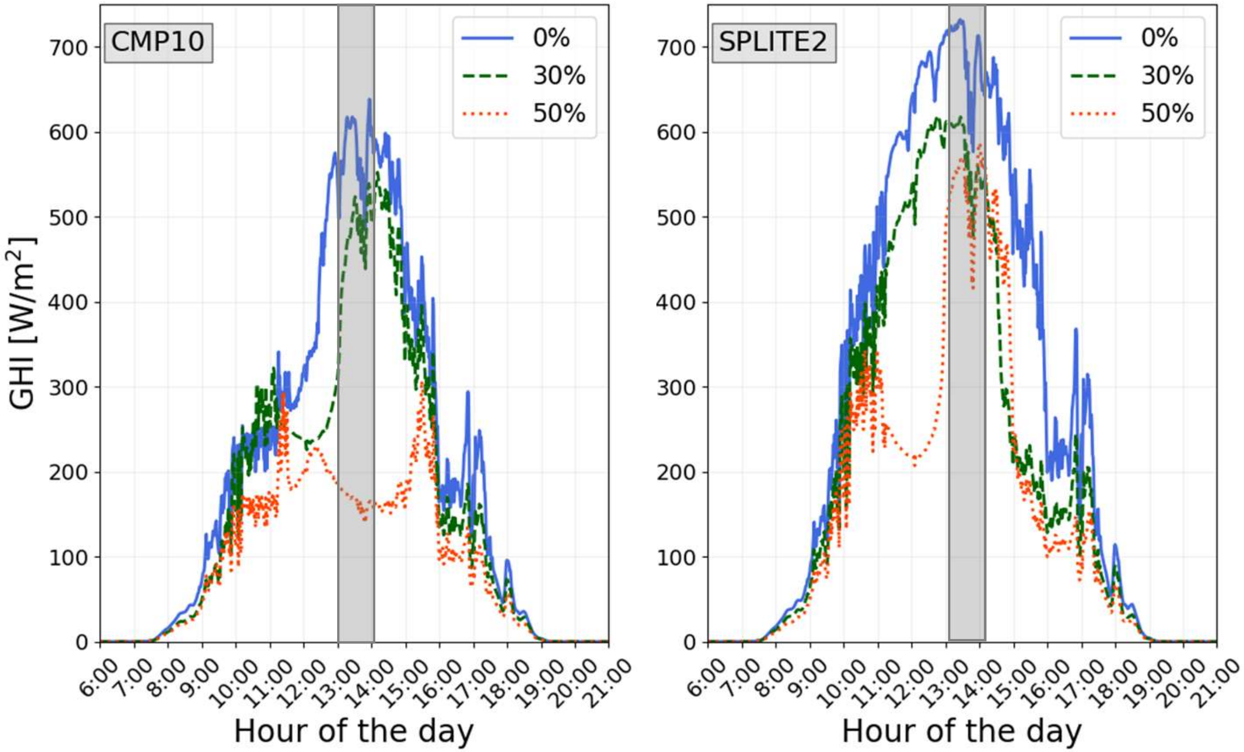

- distinct shadow pattern of individual PV modules visible in irradiance distribution
- pattern dependent on positioning of sensor w.r.t. adjacent PV modules

# Irradiance monitoring

Radiation levels close to side walls:

- comparison of pyranometers in the middle of each zone (CMP10) to at the edge of the zones (SPLITE2)
  → different patterns become dominant throughout the crop cycle

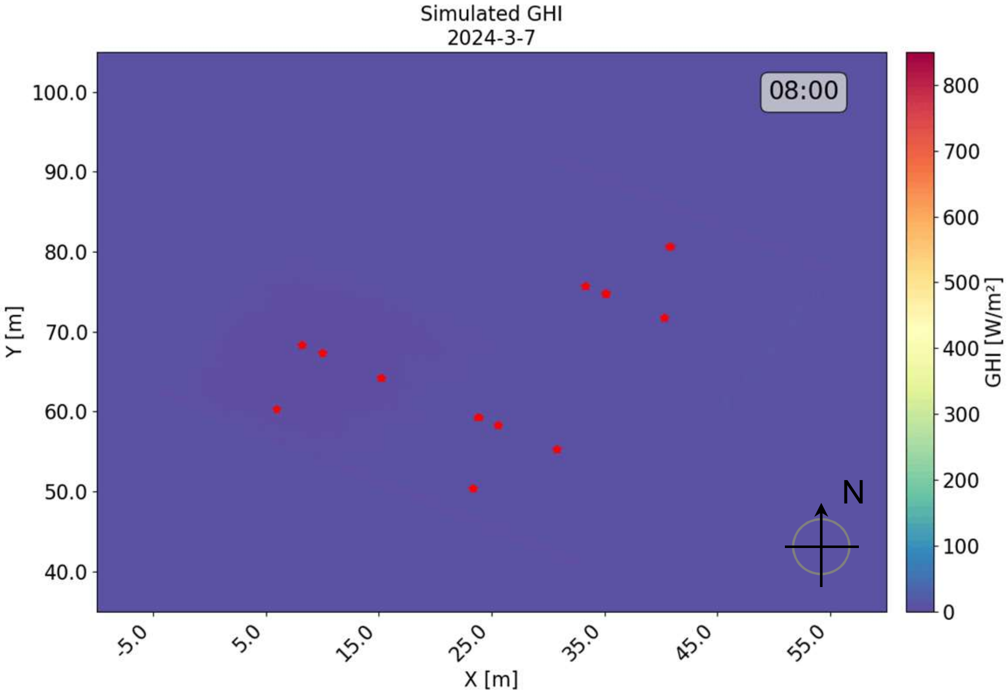



- increased irradiance from side walls in early mornings (6:00-9:00) and later half of the day (>12:00):
  - low sun angle
  - positioning of greenhouse and zones

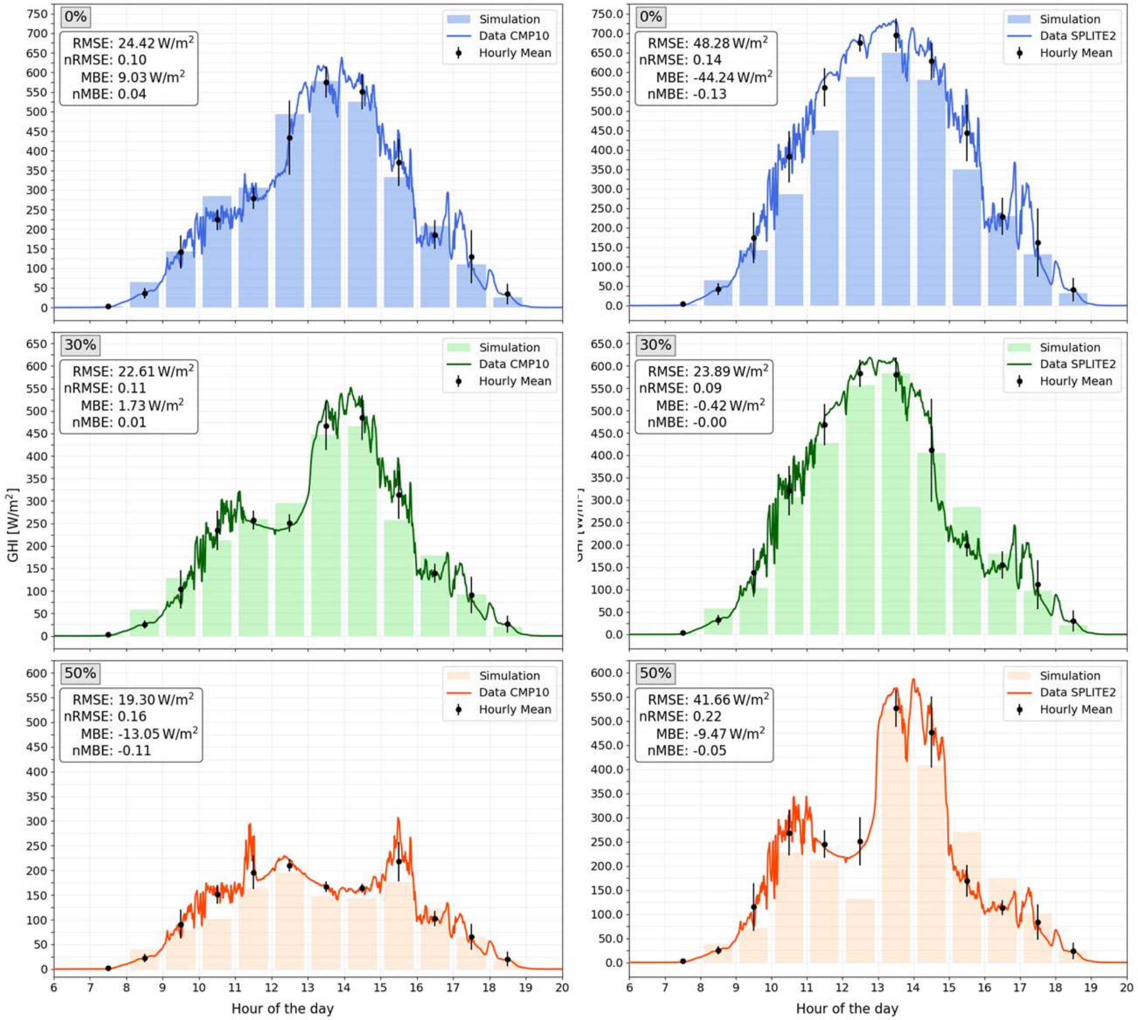
# Irradiance monitoring

Comparison Simulation – Experiment:




CMP10

SPLITE2




- simulation performed with satellite derived input irradiance data for the entire crop cycle
- model shows good agreement with experimental data for evaluated time period

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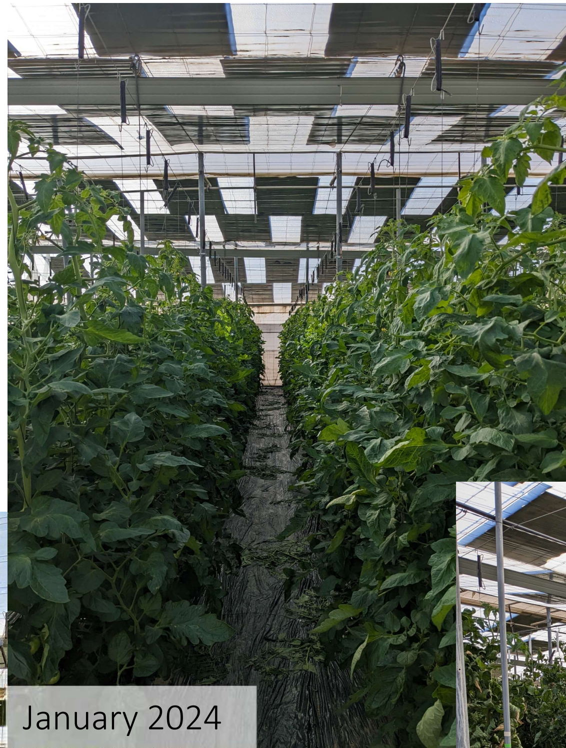
# Plant physiology and crop yield

Tomato cycle photos:

October 2023

November 2023

December 2023

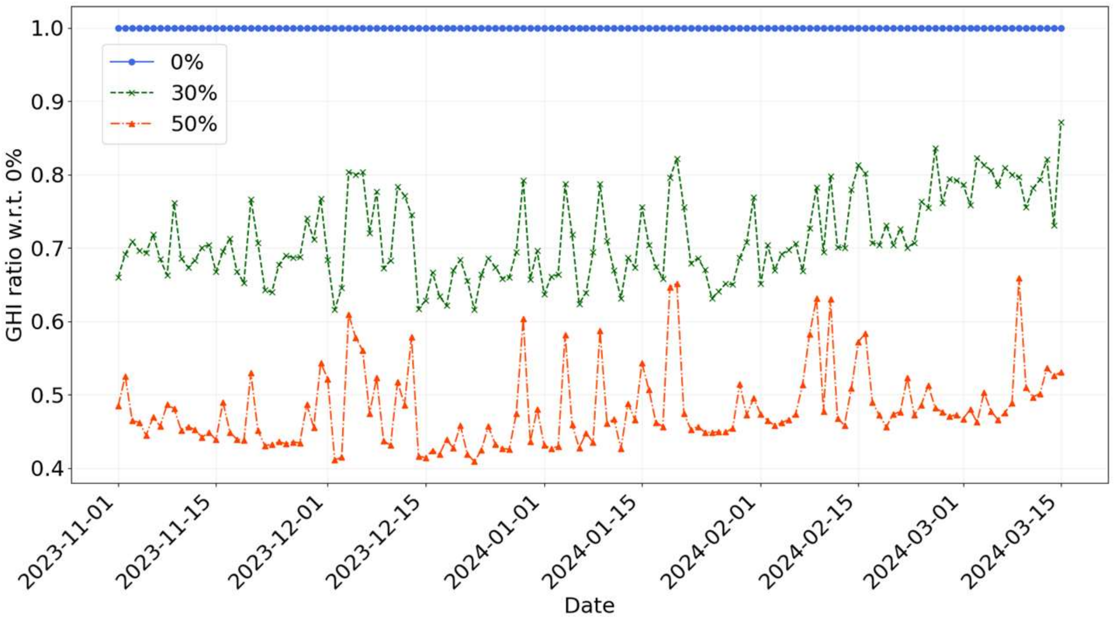


January 2024

February 2024

# Plant physiology and crop yield

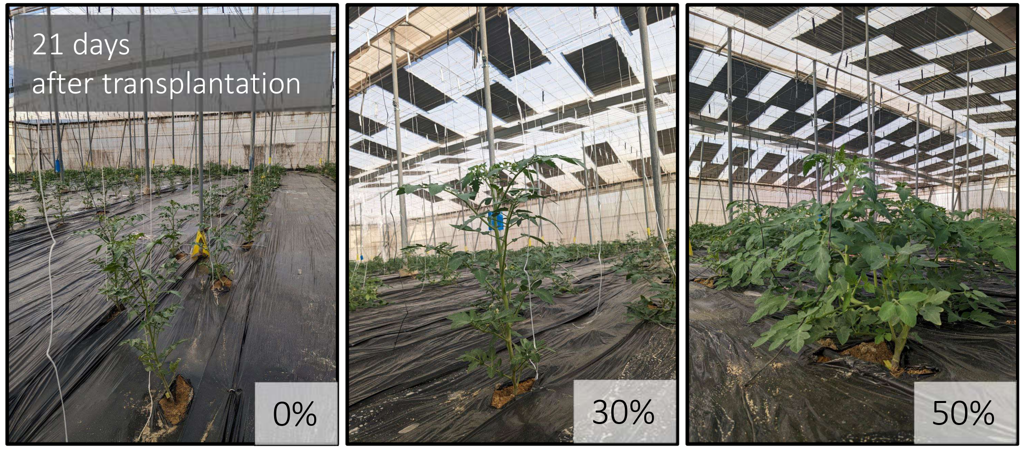
Daily sum GHI:

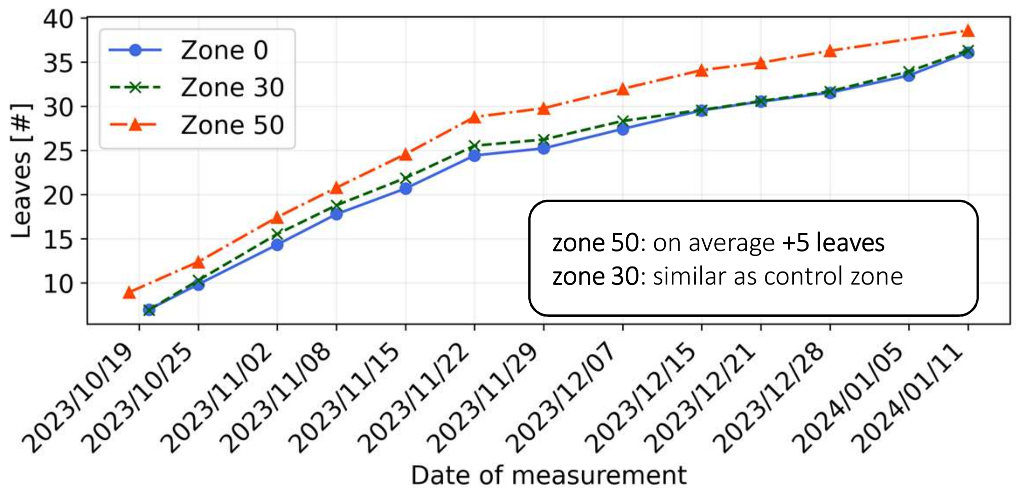



- 30% shading: GHI ratio w.r.t. control zone deviates around 30% less irradiance with an increase towards end of crop cycle
- 50% shading: GHI ratio w.r.t. control zone deviates around 50% less irradiance with a slight increase towards end of crop cycle
- → effect of etiolation [4]: i.e. elongation of stems, higher number of leaves, smaller leaves, …

[4] Burgess, J. **"An Introduction to Plant Cell Development"** (1985).

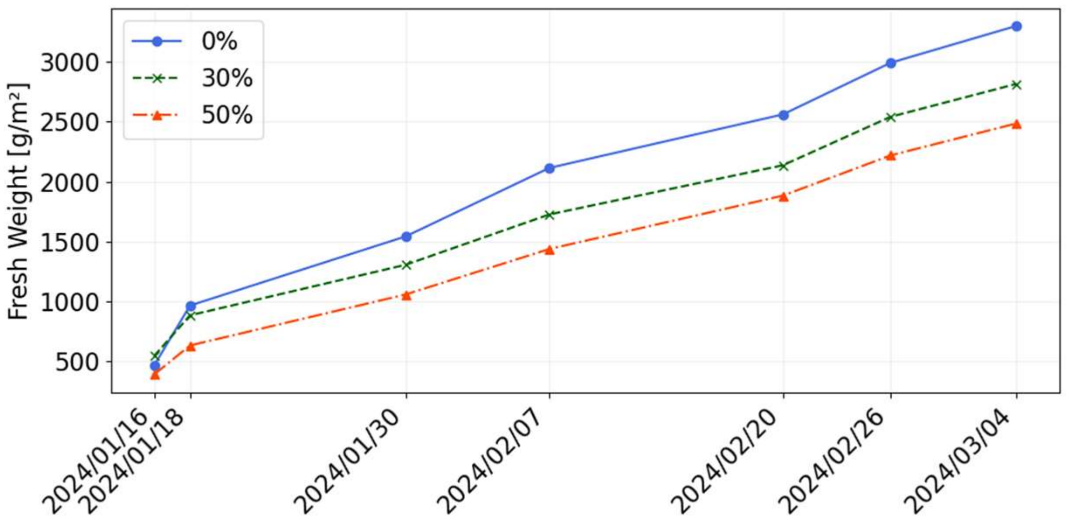
Plant physiology: number of leaves



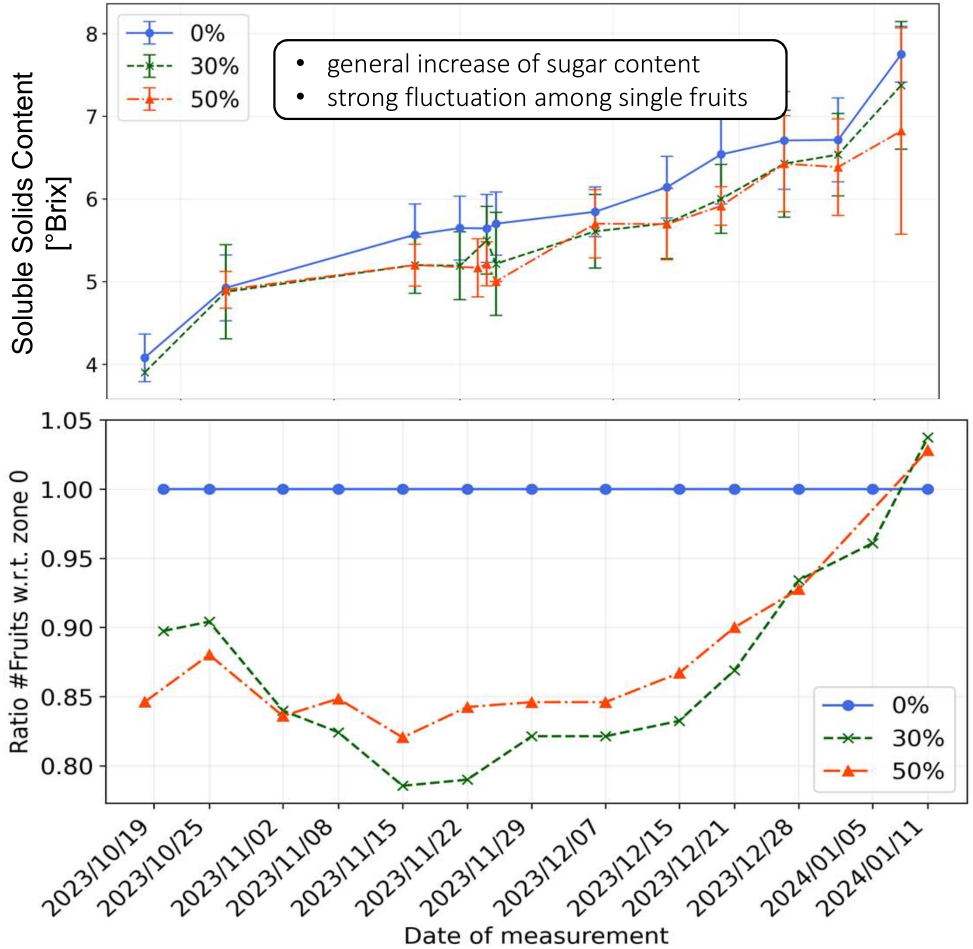
# Plant physiology and crop yield

## Fresh weight measurements:




- strongest contribution to difference at beginning of crop cycle
- zone 30: reduction of 15% at end of crop cycle
- zone 50: reduction of 26% at end of crop cycle

## Sugar content and number of fruits:



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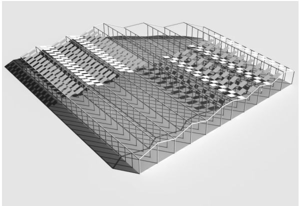
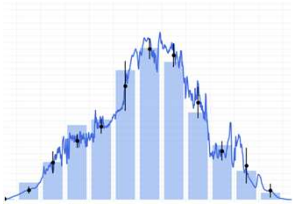
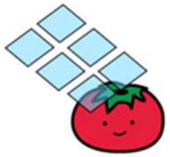


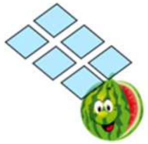
- agrivoltaic greenhouse experiment with 30% and 50% roof cover ratio in checkerboard pattern
- monitoring system presented and influence of irradiance entering through the side walls evaluated



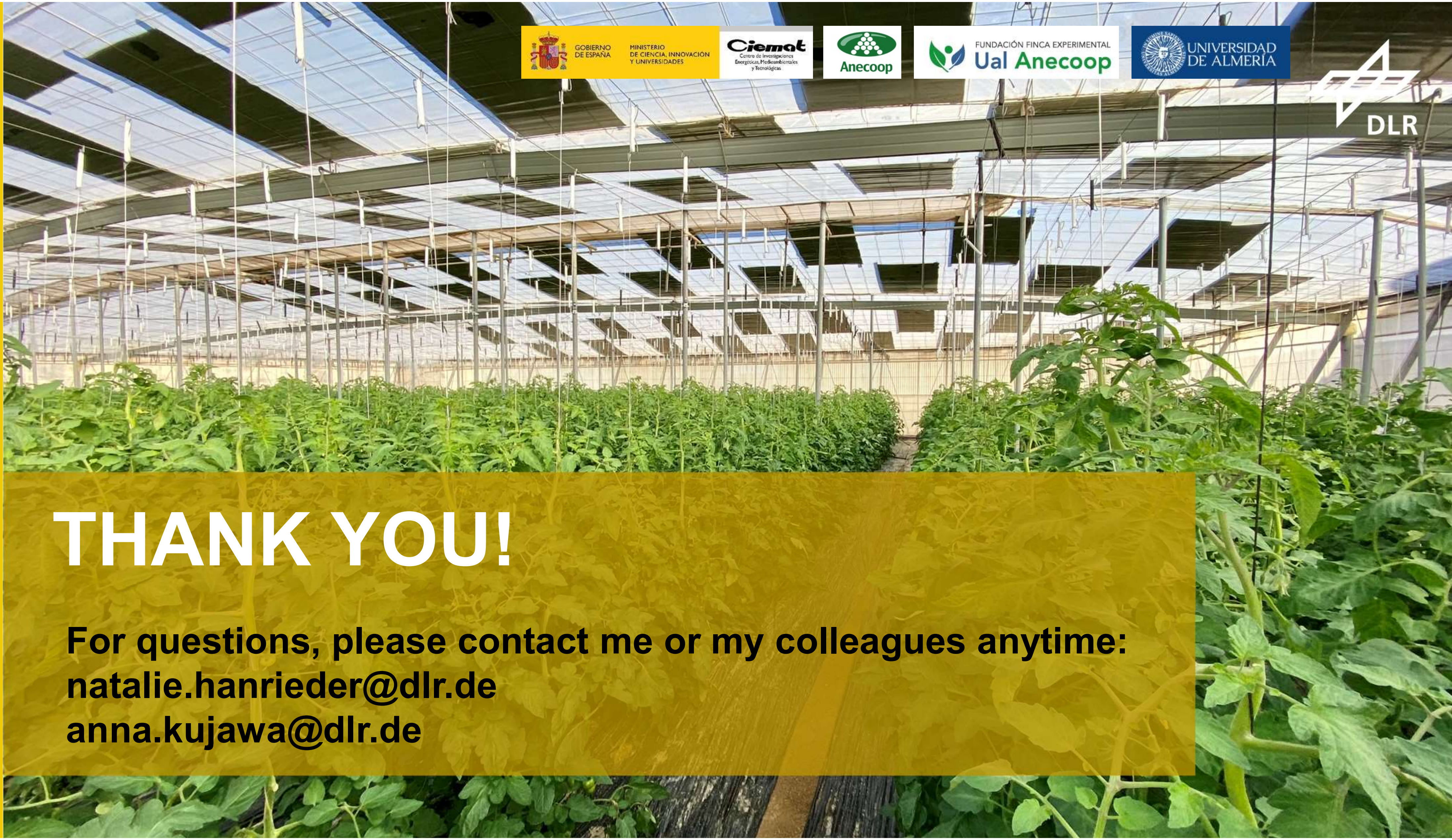
- validation of DLR's agrivoltaic model with experimental irradiance data



- plant physiology and crop yield:
  - yes, there was a yield reduction for both treatment zones (as expected)
  - increase in number of fruits toward end of crop cycle
  - strong variance in sugar content




- next steps:
  - evaluation of watermelon data
  - economic yield estimation



# THANK YOU!

**For questions, please contact me or my colleagues anytime:**
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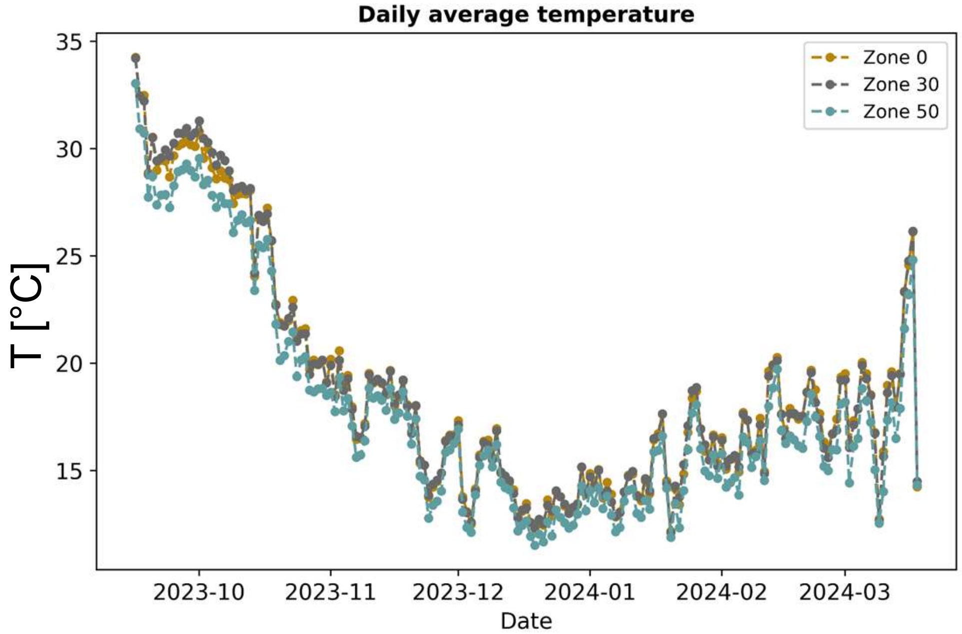
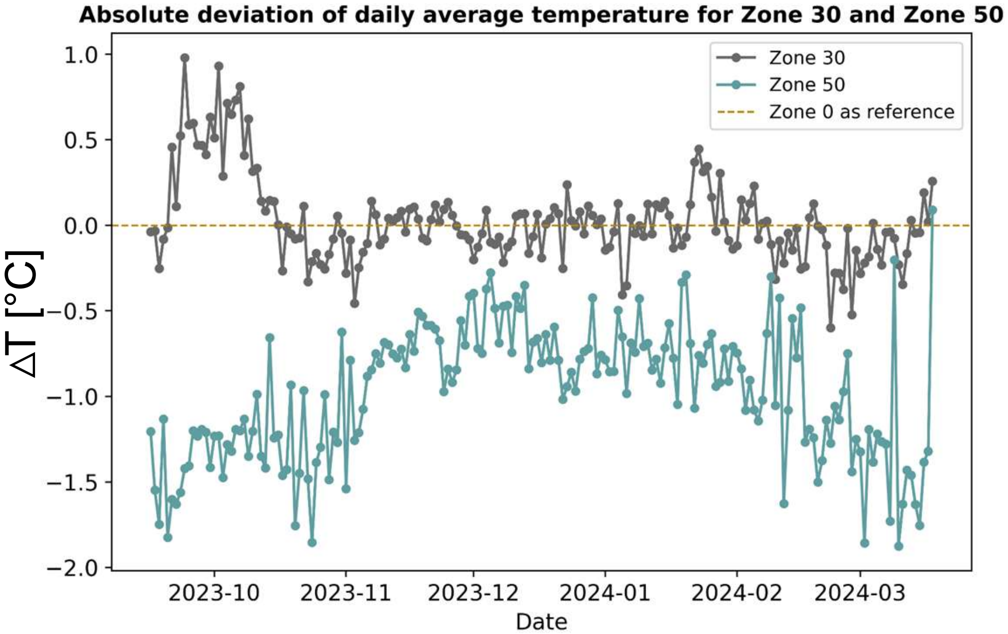
# Backup

# Microclimate monitoring

Temperature:



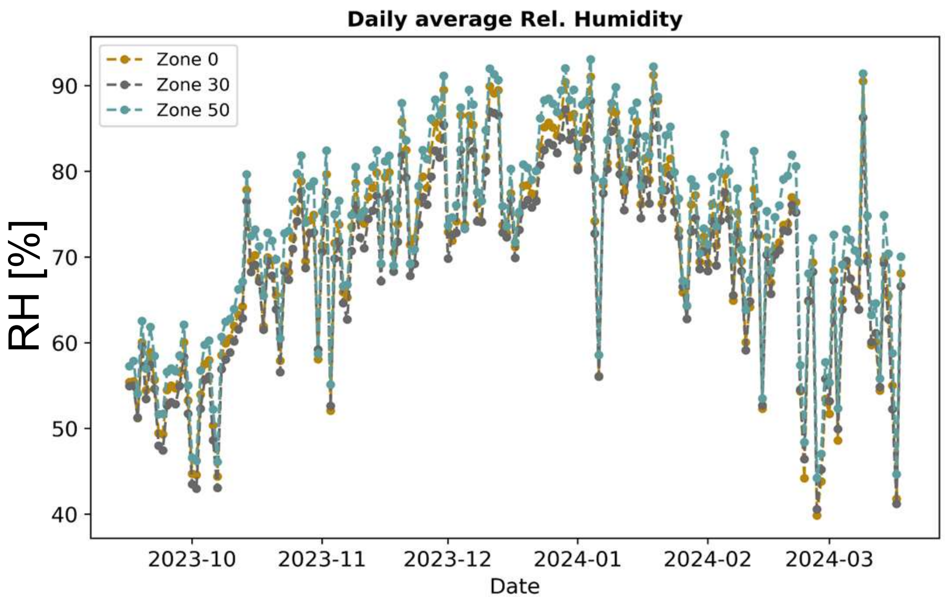

- zone 30: less than 0.3°C absolute deviation w.r.t. control for 90% of crop cycle
- zone 50: lower temperature of approx. 2°C w.r.t. control
- no physical separation of zones

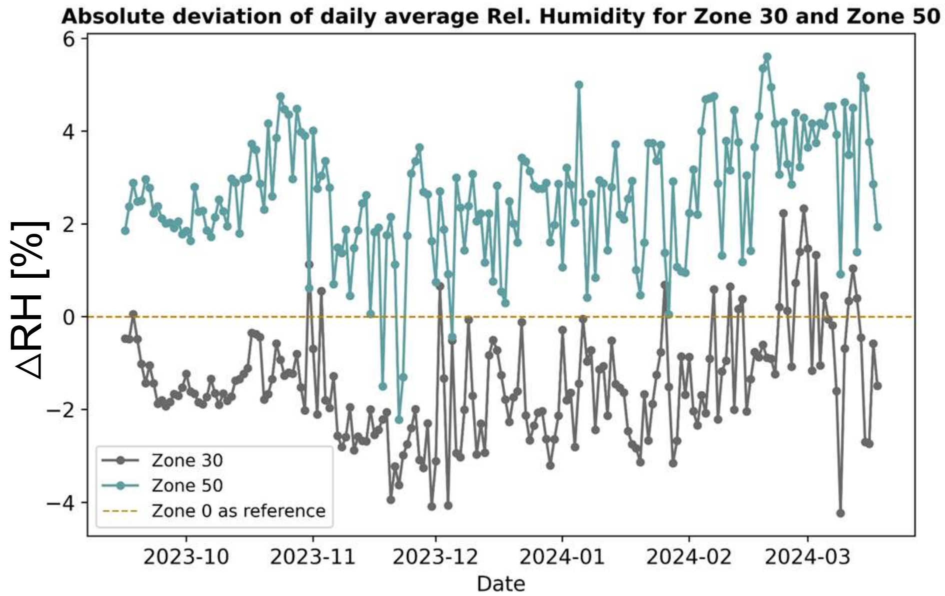
→ due to positioning of zone within greenhouse and shading of neighboring greenhouses (50% is more shaded)

→ also due to changes in plant physiology (more leaves, taller plants in zone 50)

# Microclimate monitoring

Relative Humidity:




- zone 50: overall highest relative humidity (3% higher w.r.t. control zone)
- zone 30: lowest relative humidity (on average 2% lower w.r.t. control, 5-8% lower w.r.t. zone 50)