Testing Different Shading Levels in an Agrivoltaic Greenhouse in Southern Spain

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Outline

1. Motivation: Greenhouses in Almería, Spain
2. Agrivoltaic greenhouse experiment
    1. Planning
    2. Microclimate monitoring system
    3. Tomato cycle photo story
3. Microclimate monitoring
    1. Temperature
    2. Irradiance
4. Results
    1. Daily Light Integral and height of plants
    2. Fresh weight and number of fruits
5. Summary

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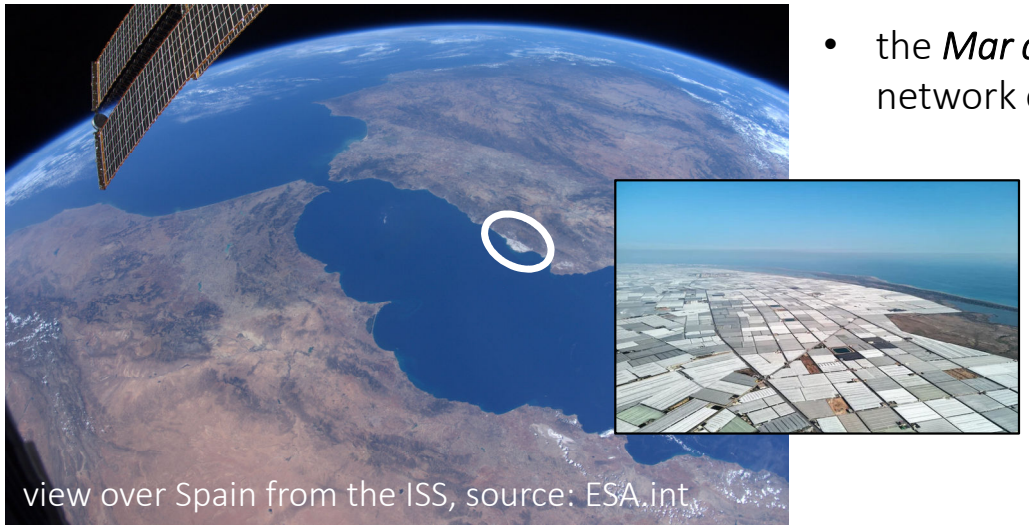
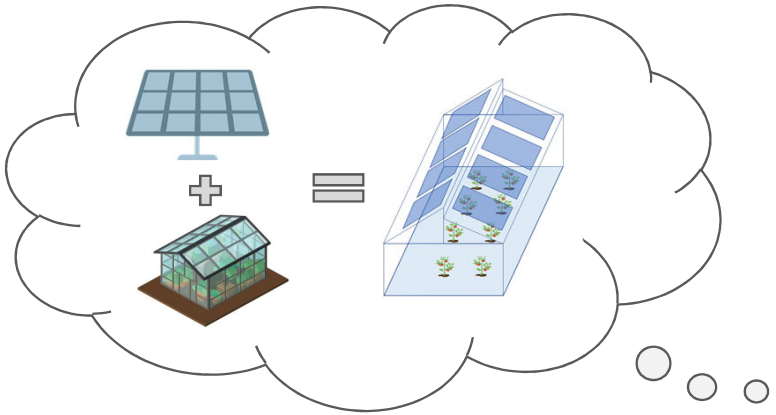
Motivation: Greenhouses in Almería, Spain


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).

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Agrivoltaic greenhouse experiment

Planning:

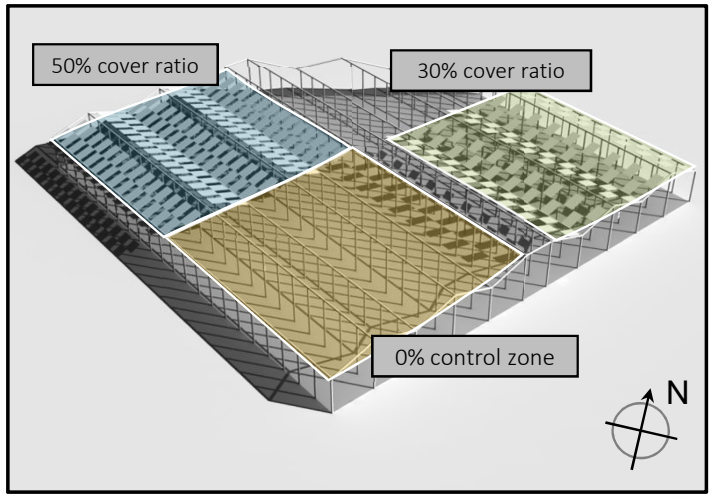
- Collaboration with company ANECOOP and Fundación ANECOOP-UAL
- August 2023: access to GH for monitoring system installation

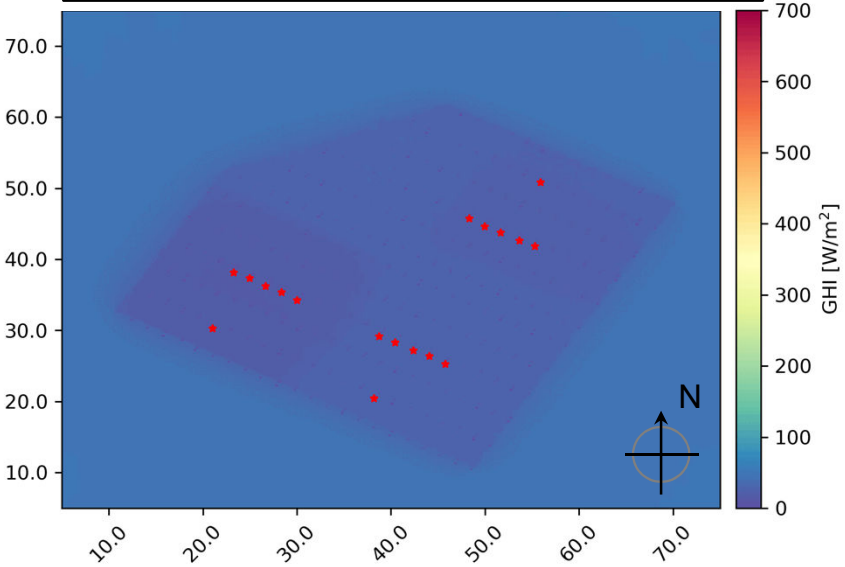
State of the art (2023):

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

Agrivoltaic greenhouse experiment

Planning:



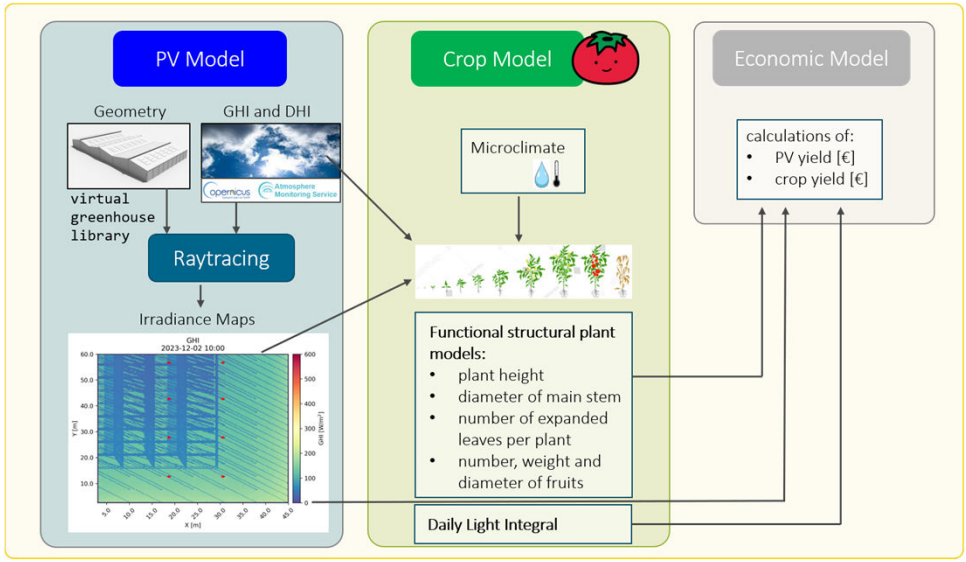


Usage of **DLR agrivoltaic greenhouse model** to define experiment:

- 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)

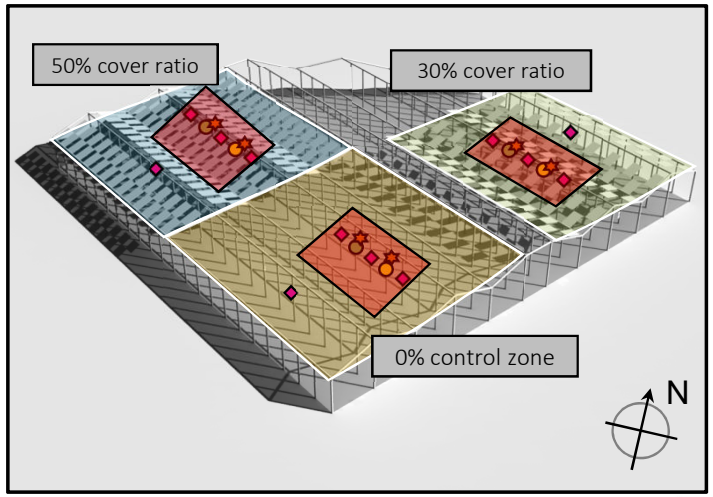
DLR's ray tracing based agrivoltaic model [3]

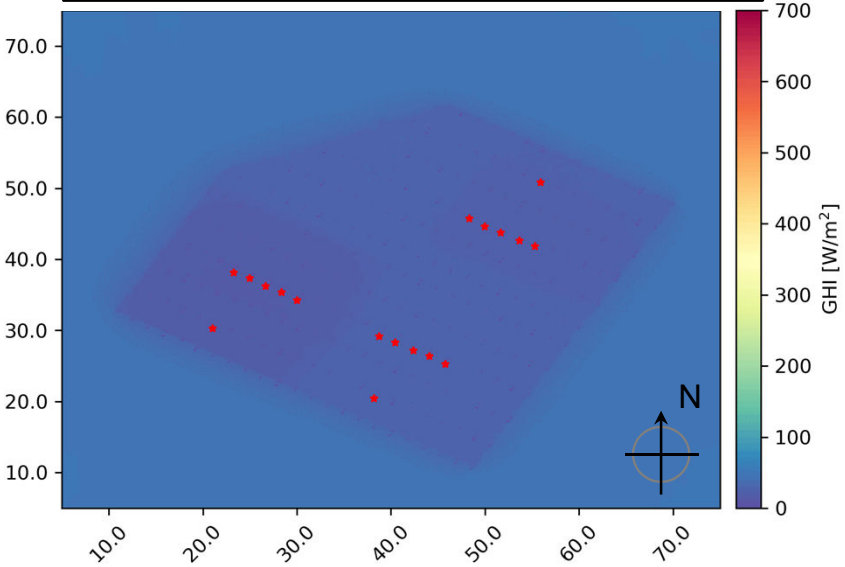


[3] Kujawa, A. et al. "**Modeling of bifacial AgriPV greenhouses in southern Spain**", EUPVSEC conference (Lisbon, 2023).

Agrivoltaic greenhouse experiment

Microclimate monitoring system:



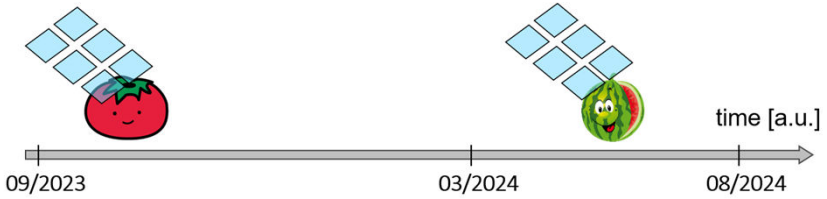


Microclimate Monitoring System

Continuous data monitoring with one-minute temporal resolution

in each zone:

- 4 pyranometers
- 1 UV-A sensor
- 1 UV–B sensor
- 2 temperature and relative humidity sensors



20 representative plants were monitored

- plant physiology
- crop yield


August 2023


100


installation of monitoring system by DLR at greenhouse of Fundación UAL-ANECOOP

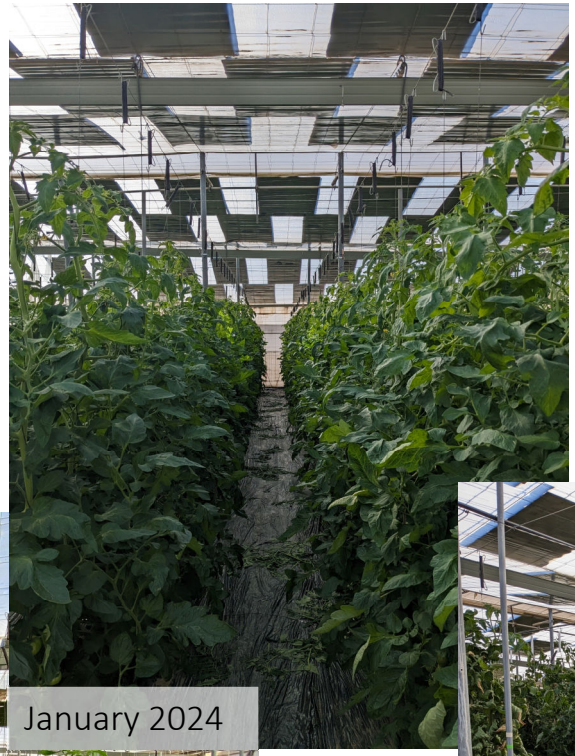
Agrivoltaic greenhouse experiment

Tomato cycle photo story:


October 2023


November 2023


December 2023


January 2024


February 2024

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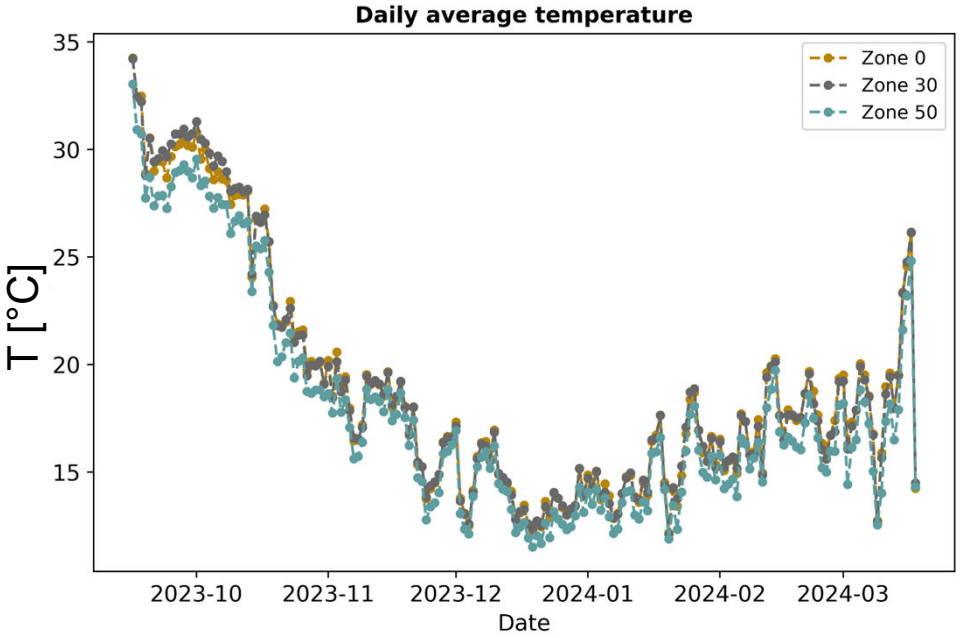
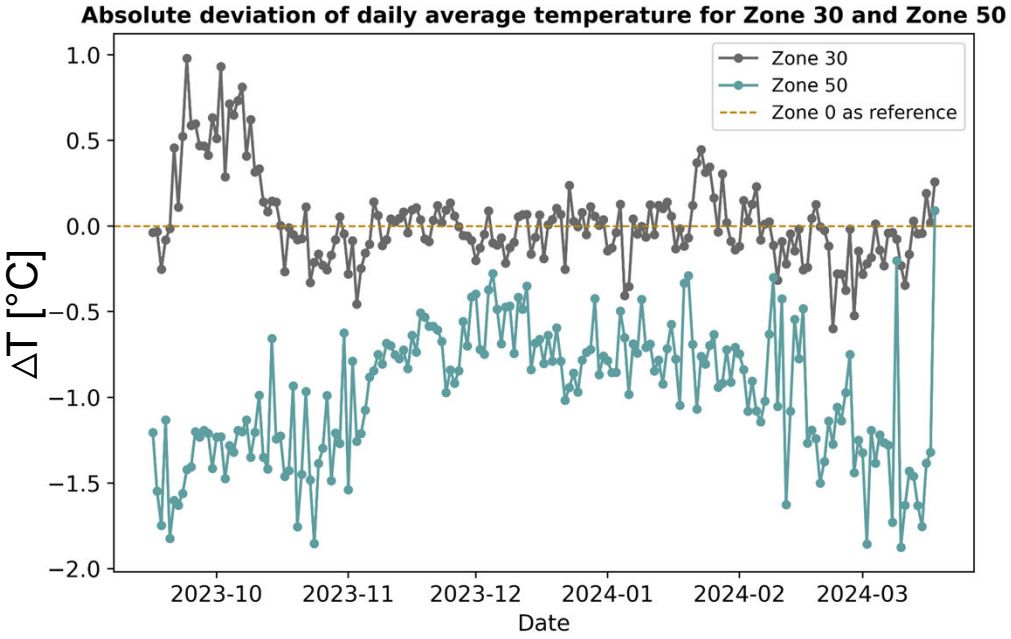
Microclimate monitoring

Temperature:





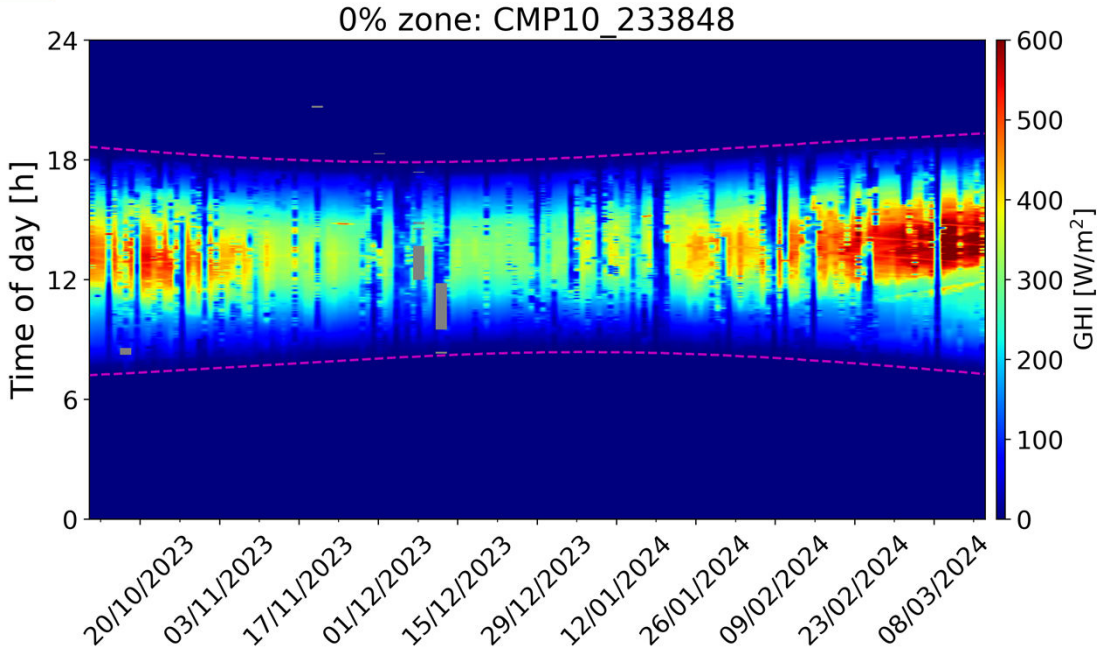
- zone 30: less than 0.3°C absolute deviation w.r.t. control for 90% of crop cycle
- zone 50: lower temperature of approx. 2°C w.r.t. control
- no physical separation of zones

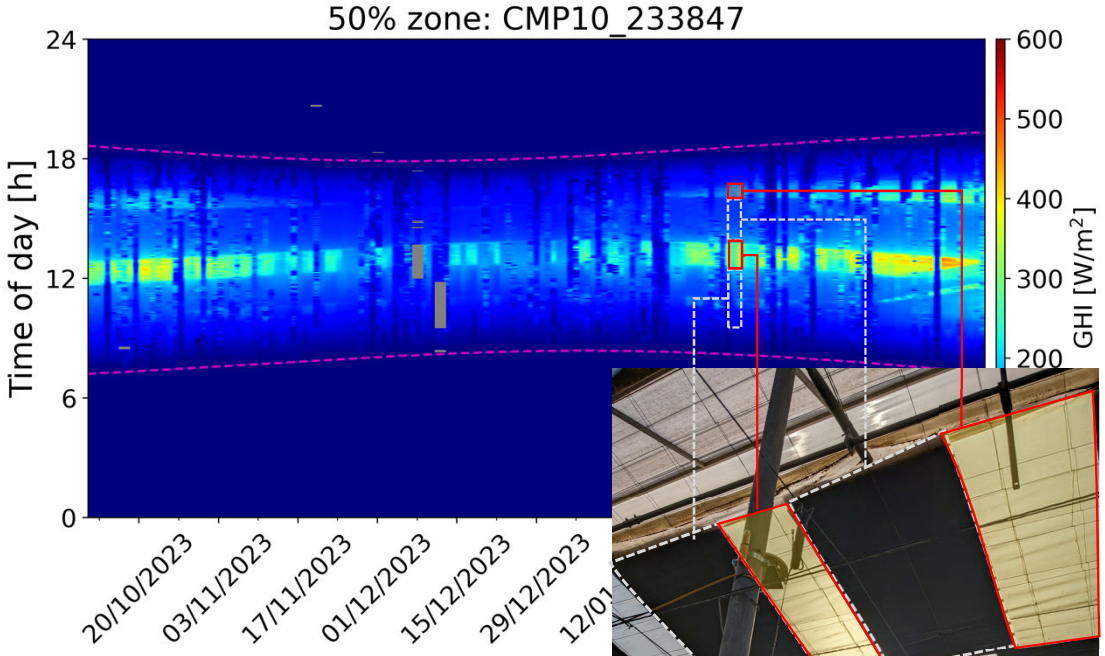
→ due to positioning of zone within greenhouse and shading of neighboring greenhouses (50% is more shaded)

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

Microclimate monitoring

Irradiance:





- distinct shadow pattern of individual PV modules visible in irradiance distribution

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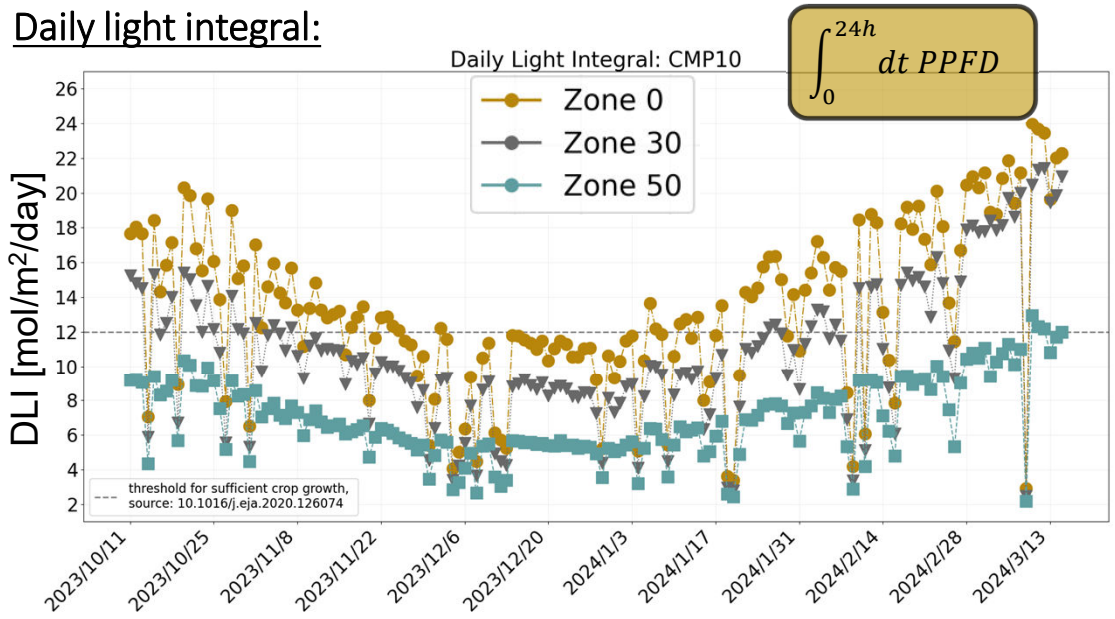
Results

Daily light integral:

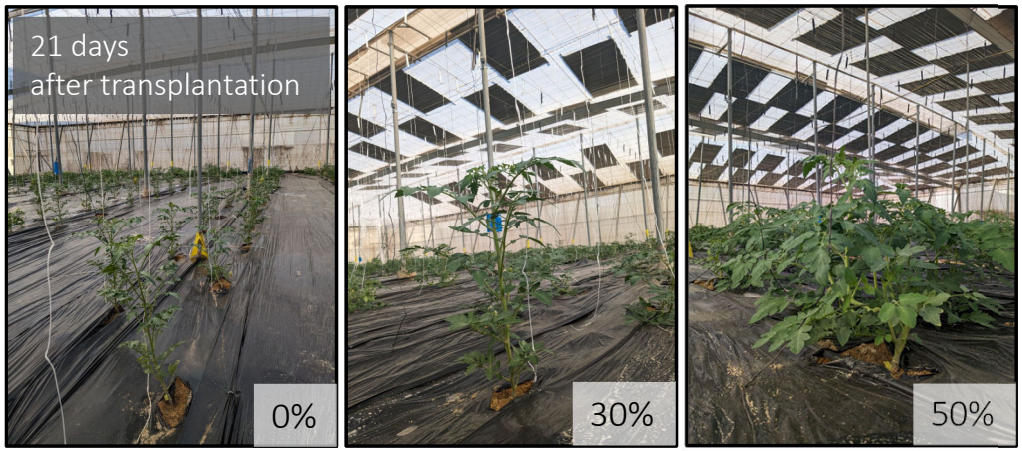


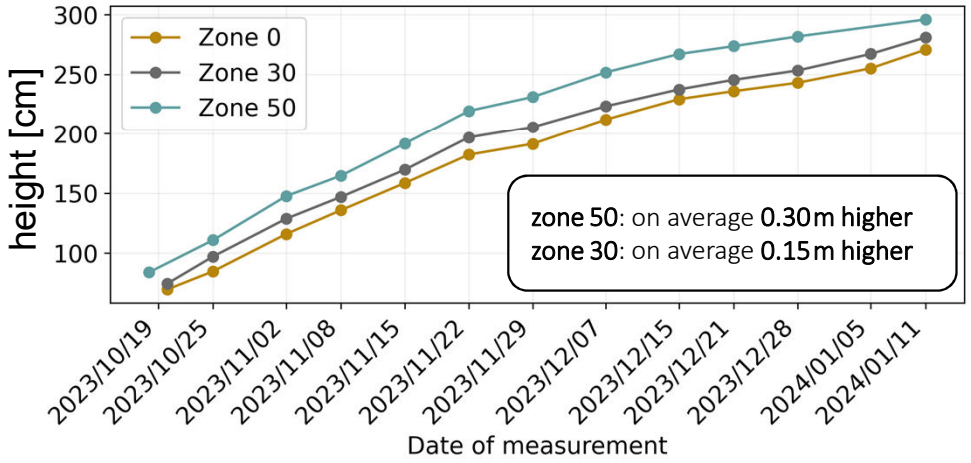
→ calculation of photosynthetic photon flux density (PPFD) and integration over one day results in the daily light integral (DLI) [4]

- DLI threshold for sufficient crop growth for tomatoes ~12 mol/m²day [4]
- resulting in visibly different plant development already after first few days of crop cycle
- → effect of **etiolation [5]:** i.e. elongation of stems, higher number of leaves, smaller leaves, …

[4] Cossu, M. et al. **"Agricultural sustainability estimation of the European photovoltaic greenhouses"**, European J. of Agronomy (2020).
[5] Burgess, J. **"An Introduction to Plant Cell Development"** (1985).

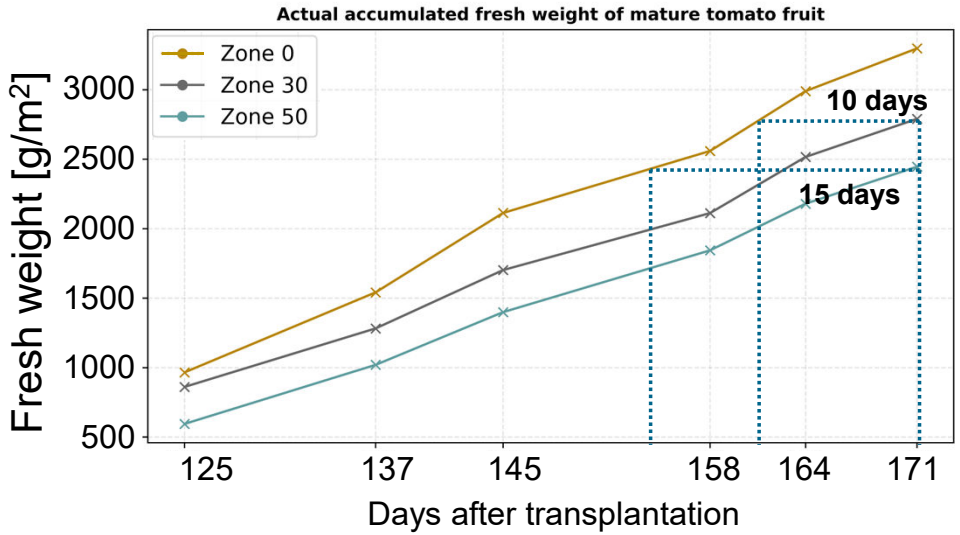
Plant physiology: height of tomato plants





Results

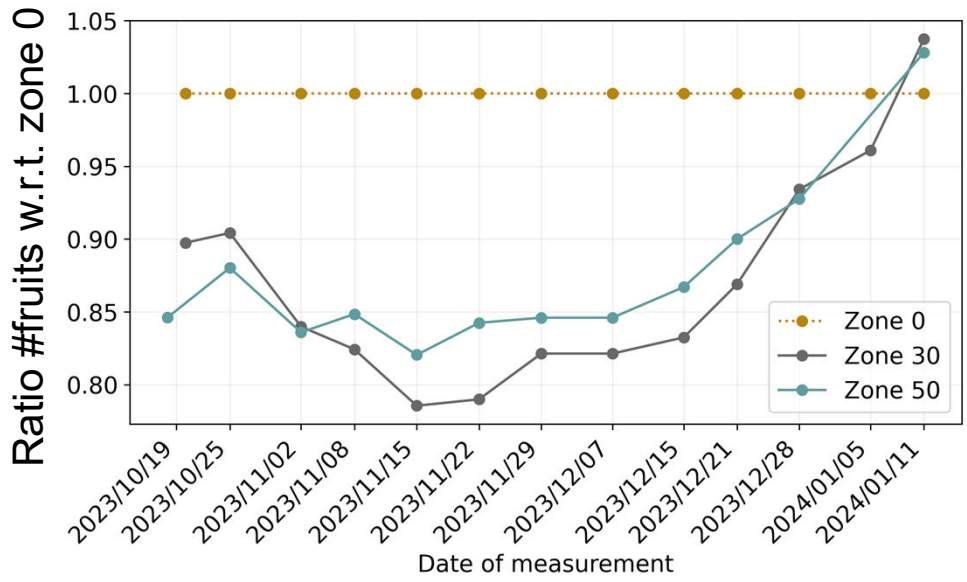
Fresh weight measurements:



- strongest contribution to difference at beginning of crop cycle
- **zone 30**: reduction of 500 g/m² or **15% at end of crop cycle**
- **zone 50**: reduction of 850 g/m² or **26% at end of crop cycle**

- **zone 30**: **delay of yield of approx. 10 days w.r.t. control zone** at end of crop cycle
- **zone 50**: **delay of yield of approx. 15 days w.r.t. control zone** at end of crop cycle

Number of fruits:



- zone 30: 10 % less fruits at start of fruit production
- zone 50: 15% less fruits at start of fruit production
- **general increase in number of fruits for zone 30 and 50**
- **4% more fruits in zone 50 and 30 at end of growing period**

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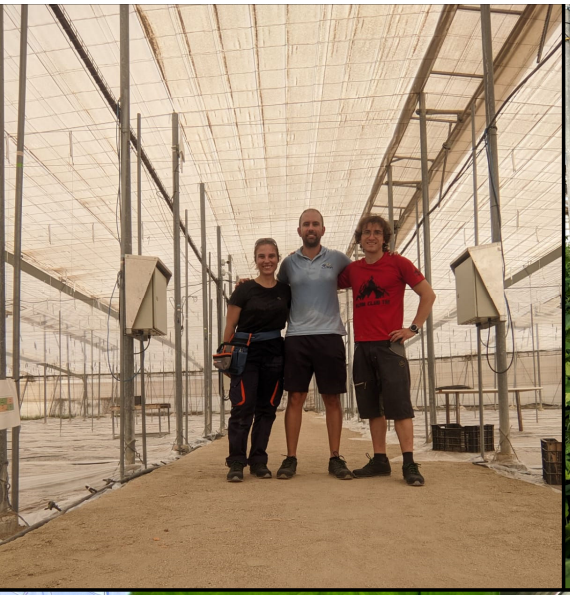
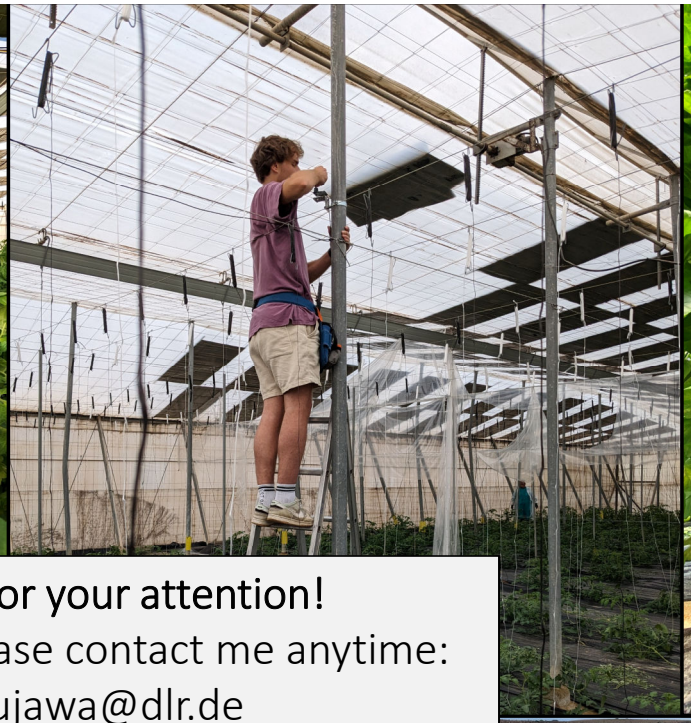
Summary

- agrivoltaic greenhouse experiment with 30% and 50% roof cover ratio in checkerboard pattern
- tomato growing season from September 2023 to March 2024
- microclimate measurements presented
- crop yield results:
  - yes, there was a yield reduction for both treatment zones (as expected)
  - delay in yield:
    - zone 30: 10 days w.r.t. control zone
    - zone 50: 15 days w.r.t. control zone
  - increase in number of fruits toward end of crop cycle
- several more plant physiology and yield quality parameters measured
  - plant physiology (number of branches, length of branches, number leaves, size of the leaves, diameter trunk)
  - fruit dimensions (width, length, dimension inner wall,…)
  - fruit durability
  - sugar content

- informal quality control: approved by colleagues

agrivoltaic tomato taste test at DLR's office party






Thank you for your attention!
For questions, please contact me anytime:
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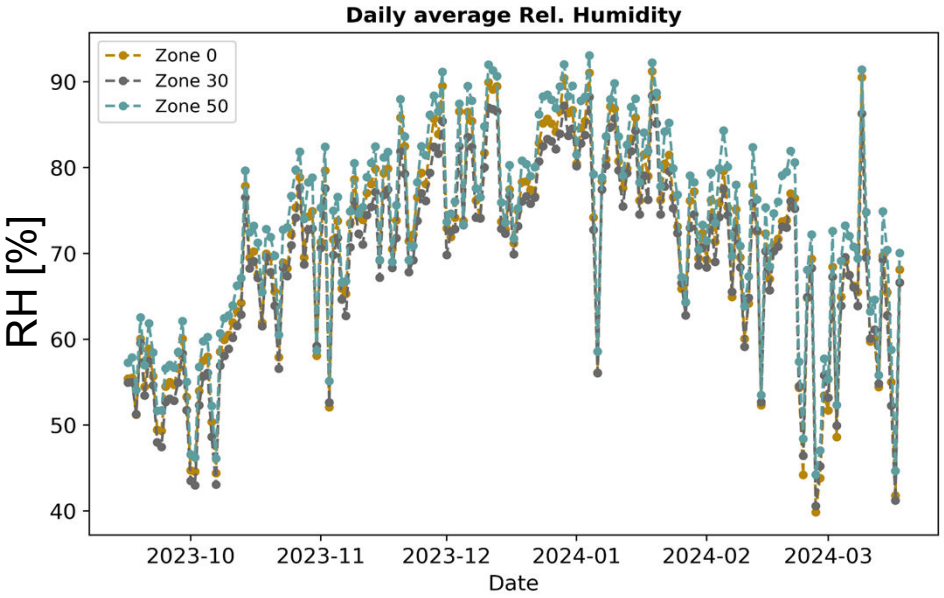
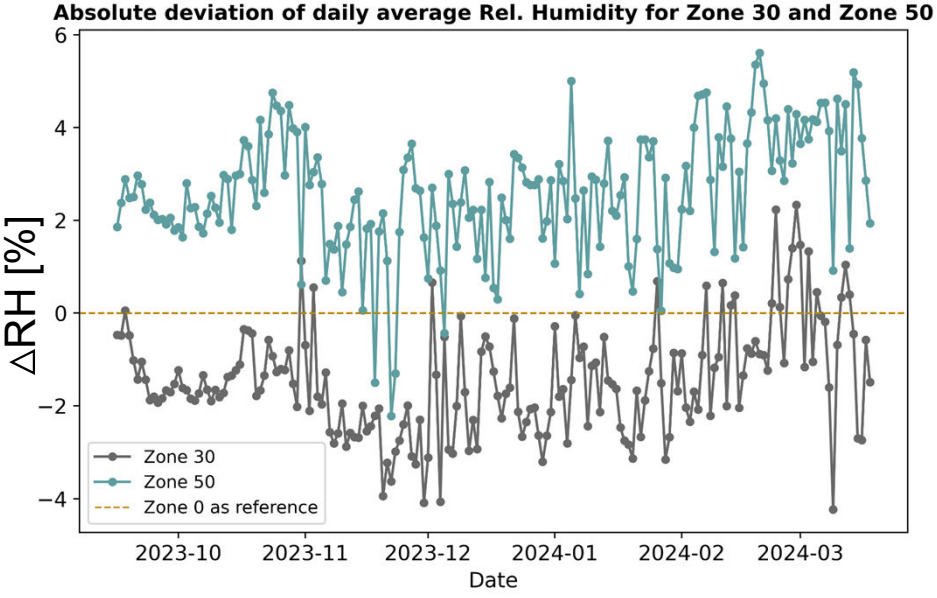
Backup

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)