Remote Sensing for Precision Agriculture in Agrivoltaics

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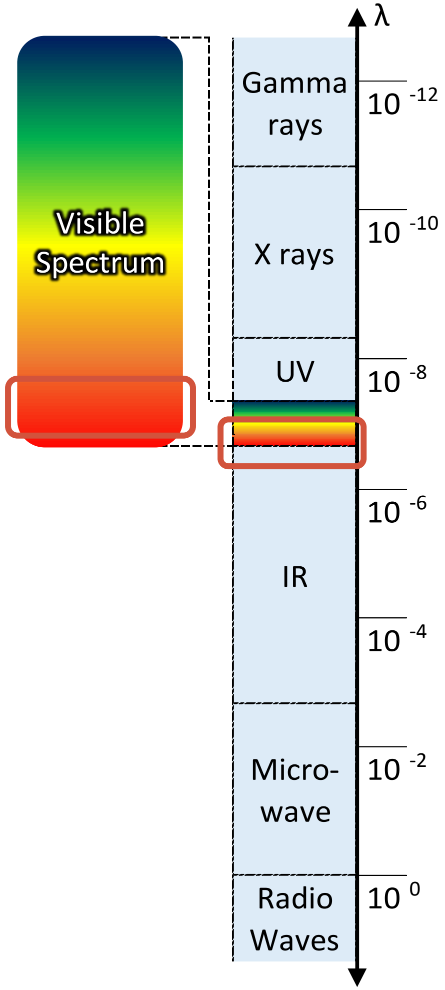
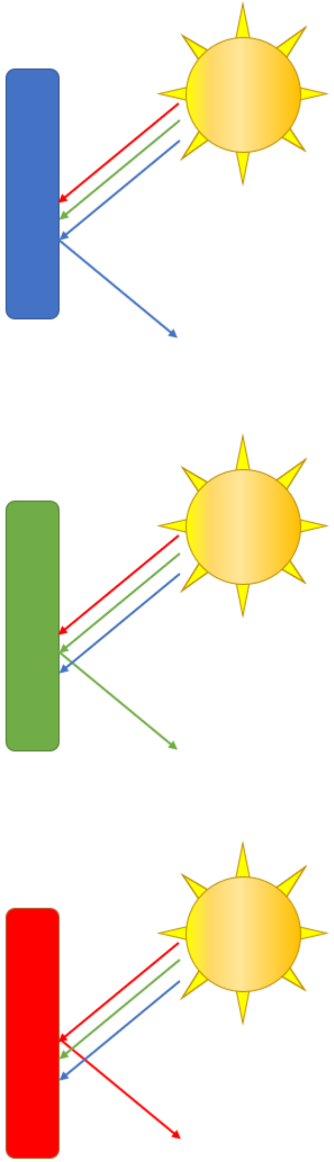


Remote Sensing



What is "Remote Sensing"?

- the acquisition of information about objects from a **distance**.
- It allows obtaining information quickly, objectively, and non-destructively ➔ perfect for **Precision Agriculture.**
- The information reflected/emitted by objects is used. The color and radiation that objects reflect or emit are received by sensors, and this depends on the material's absorption spectrum.

It uses information from the electromagnetic spectrum:

- **Visible light.** Approximately between 0.4 and 0.7 micrometers in wavelength.
- Other regions of the electromagnetic spectrum are **not visible** to the human eye but are detectable by different sensors (e.g., NIR, thermal, etc.).
- The information is separated into different bands (red, blue, green, infrared…) to facilitate its study and analysis ➔ Vegetation Indices (NDVI).

What are the applications?

Mapping of the World’s Forests

Earth's Carbon Cycle

Climate Change

Atmospheric Changes and Air Quality

Tectonic or Seismic Activity

Movement/Variation of Glaciers

Exploitation of Natural Resources

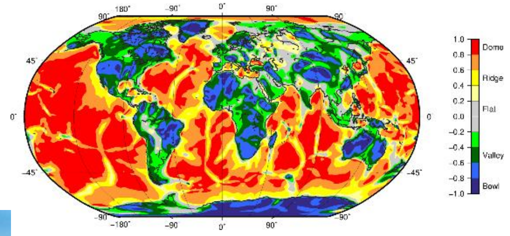
Identification of New Deposits

Urban Expansion

Natural Disasters

Floods, droughts, fires…

Crop Yields



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Precision Agriculture

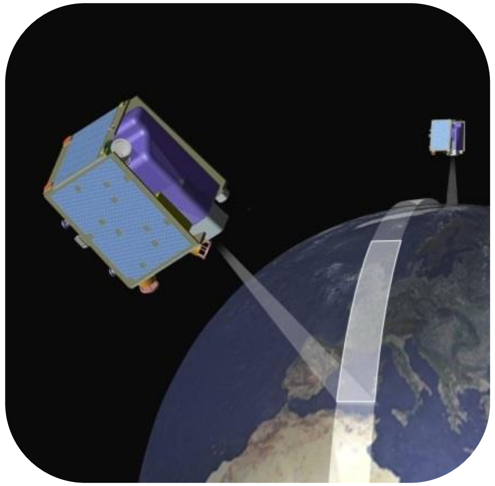
Precision Agriculture

- Precision agriculture uses technology like GPS, sensors, and data analysis to optimize farming practices by targeting inputs (water, fertilizer, etc.) to specific field areas. This increases efficiency, reduces waste, and improves crop yields. It also promotes sustainability by minimizing environmental impact.
- Today, remote sensing is a key element of precision agriculture.

Why is it important? - Benefits of Precision Agriculture

- Improved Efficiency
- Higher Yields
- Environmental Sustainability
- Better Decision-Making

First: How to obtain images?



VS

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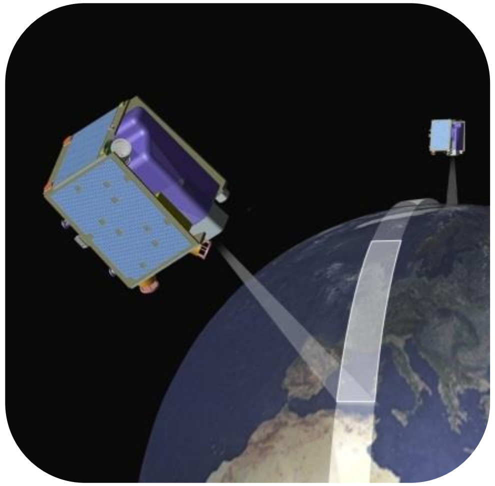
How to obtain images?



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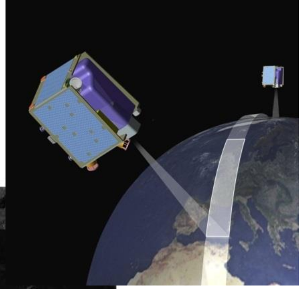
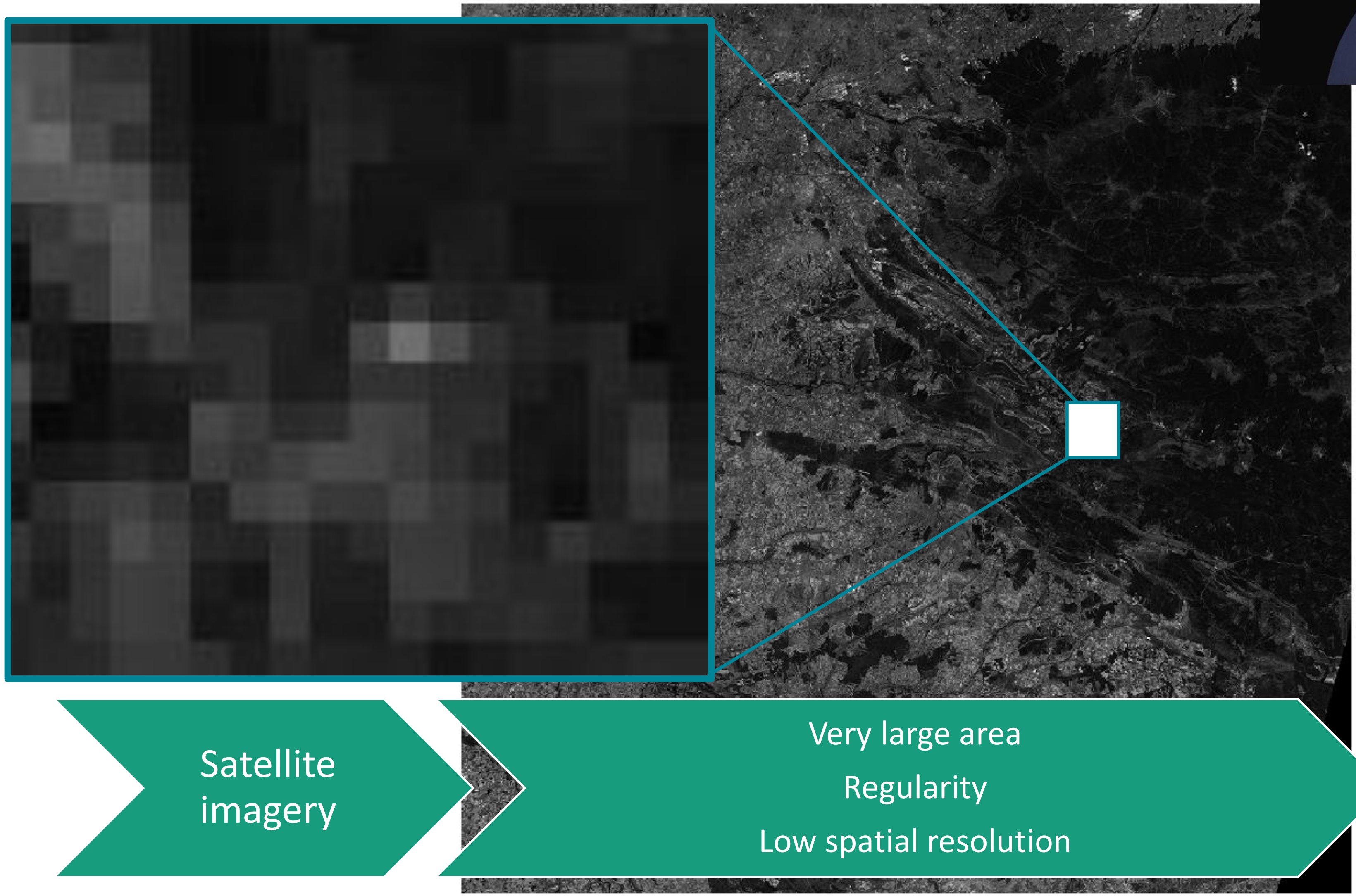
Platforms - Satellites





Satellite imagery

Very large area

Regularity

Low spatial resolution

Platforms - Satellites

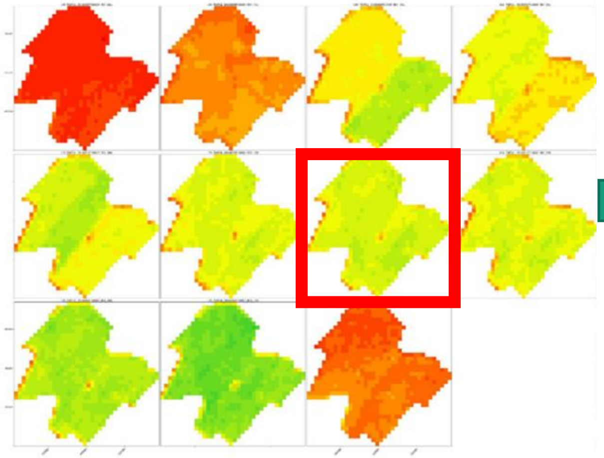


Fig. 1: Cloud-free NDVI images. High vigour vineyard.

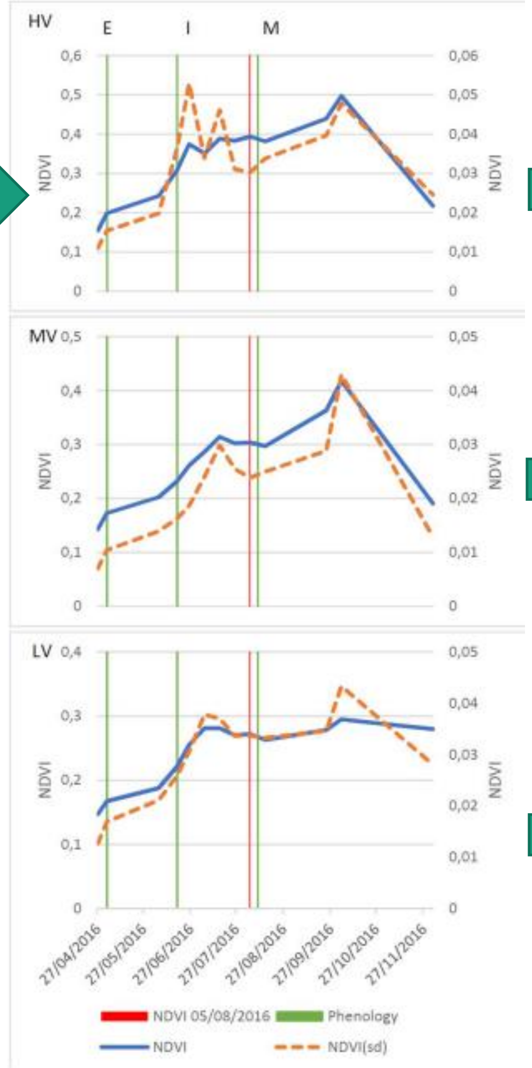


Fig. 2: NDVI evolution and standard deviation (NDVI, sd) of e vineyard. High, medium and low vigour (top to bottom).

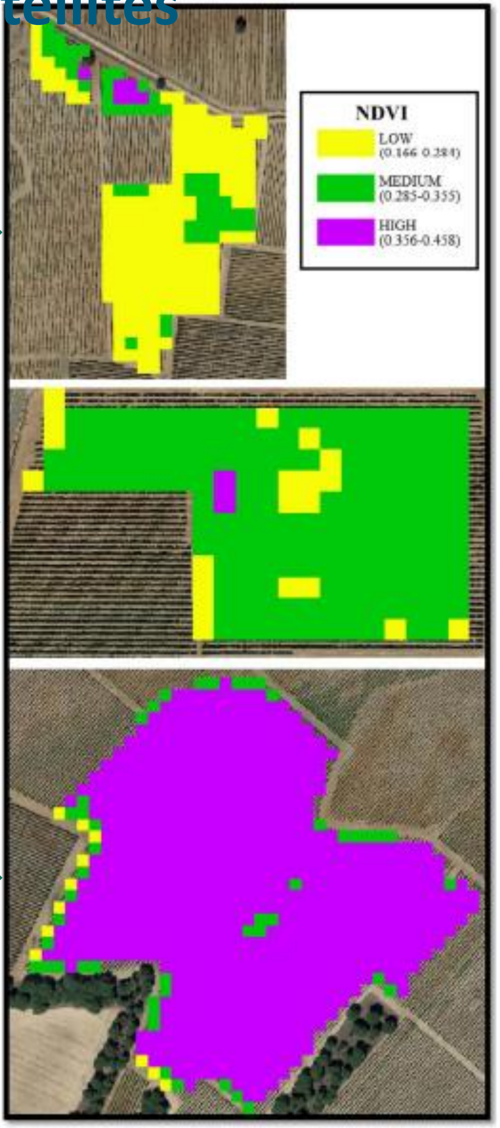


Fig. 3: NDVI classification between vineyards. 3 vigour levels: low, medium and high (top to bottom).

- when using satellite imagery we have the advantage of studying several plots at the same time.
- We usually use only one image, which coincides with the ripening of the fruit (in summer).
- We can perform time series analysis

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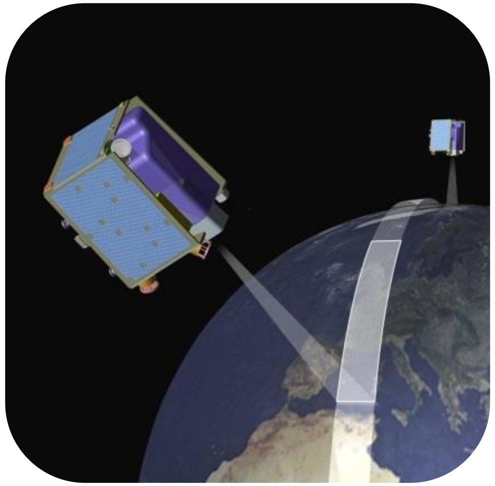
How to obtain images?



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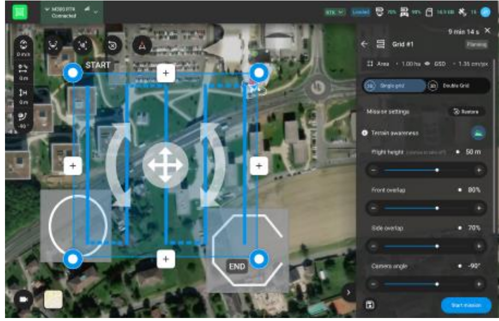
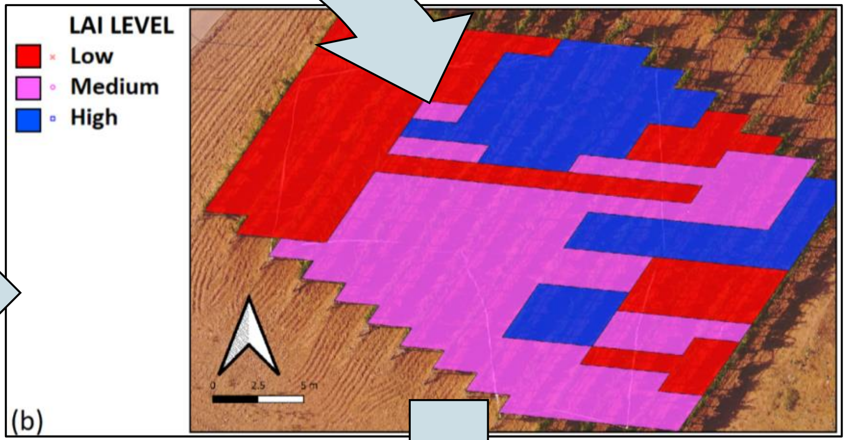
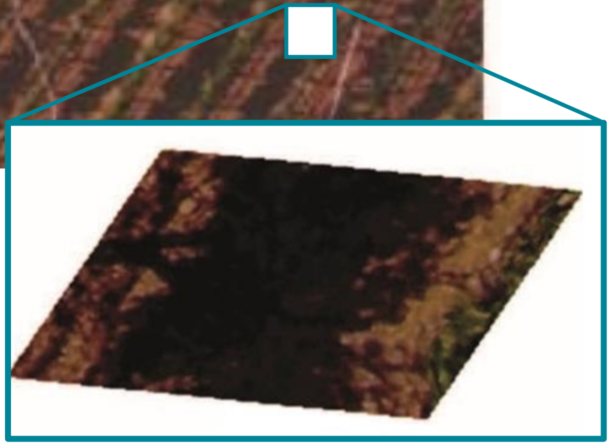
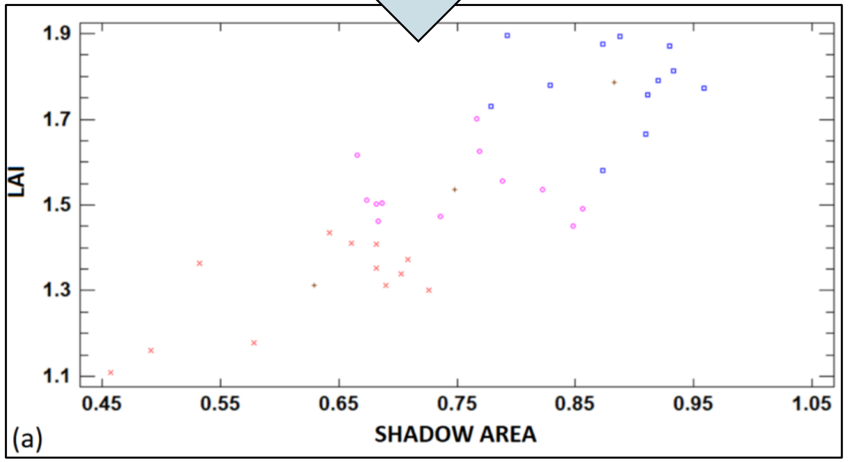
Drones flying over the field



Platforms – Drones or UAVs







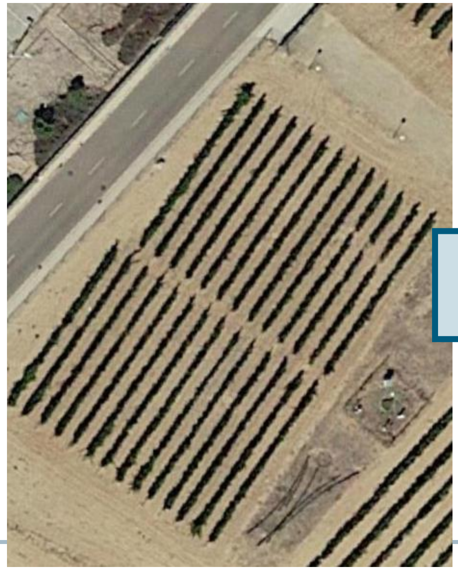
High spatial resolution

Reduced area

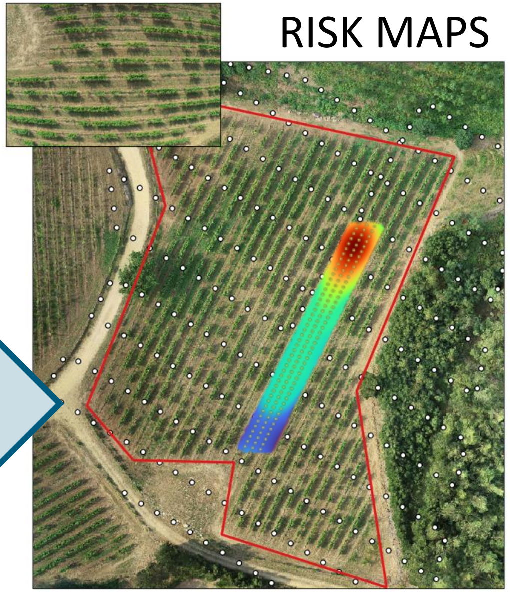
Higher operational cost - Regularity

Maps - Orthomosaics

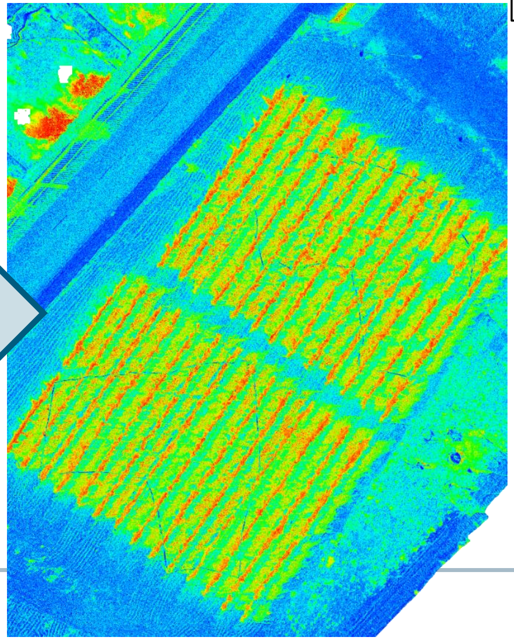
Maps - Orthomosaics

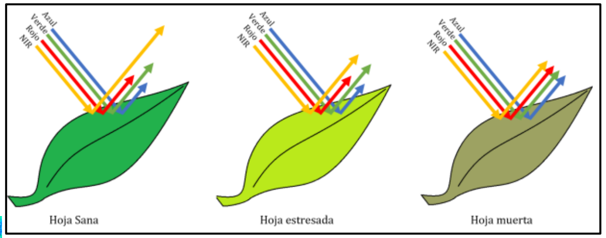


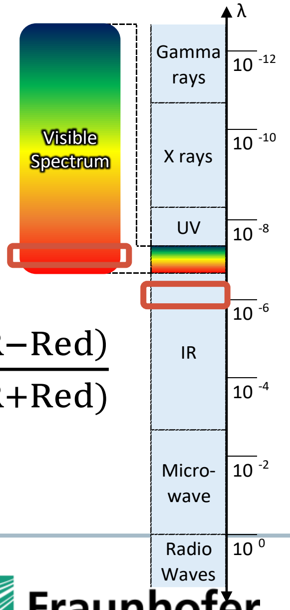
RISK MAPS



VEGETATION INDICES







$$\text{NDVI} = \frac{(\text{NIR}-\text{Red})}{(\text{NIR}+\text{Red})}$$

Maps - Orthomosaics

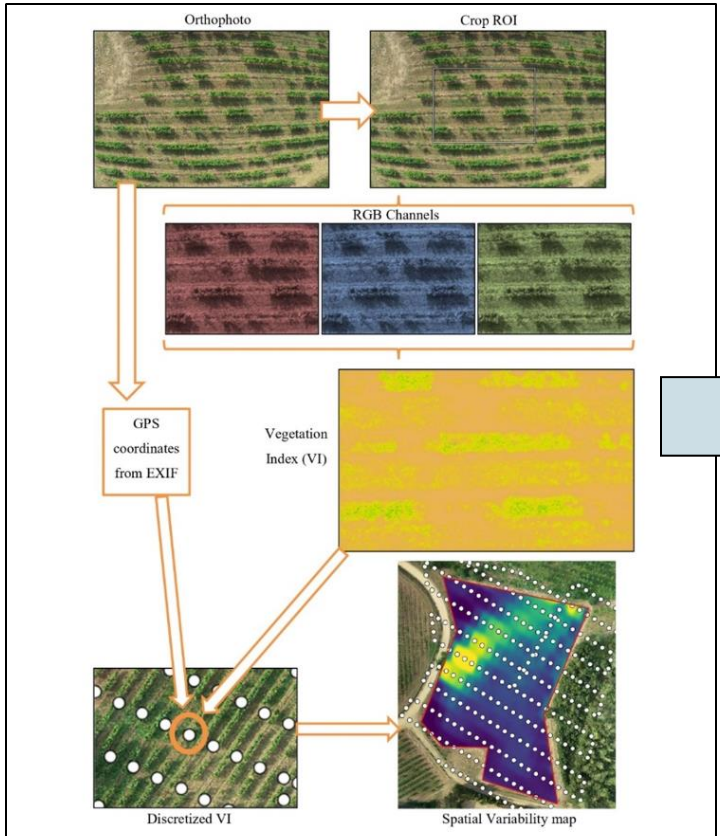


Fig. 8. – Workflow including the generated product for the experiment in the vineyard. The initial inputs are the nadir images from the UAV flight. The Vegetation Index is calculated and discretized using the coordinates extracted from the metadata of each image. Finally, spatial interpolation is performed in order to generate the spatial variability map.

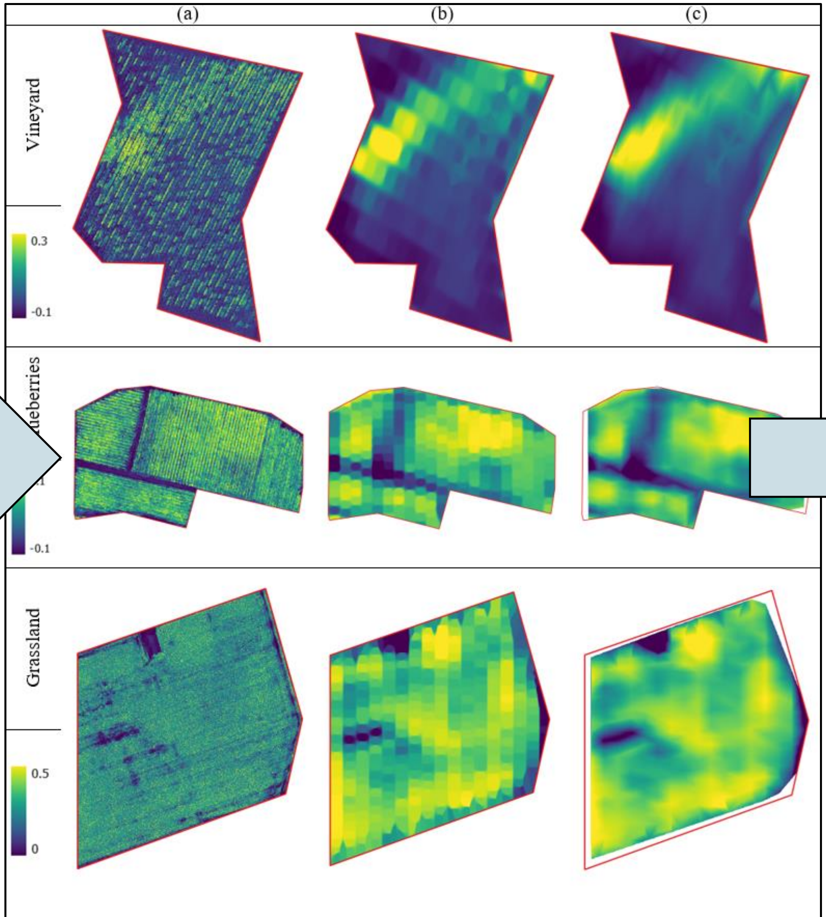


Fig. 9. – Spatial variability maps based on Normalized Green-Red Difference Index (NGRDI) for each location generated using (a) orthomosaic, (b) optimized IDW, and (c) linear TIN for each field. The position of the cameras and the drone flight conditions were different in each field. WGS84 Pseudo-Mercator (EPSG: 3857).

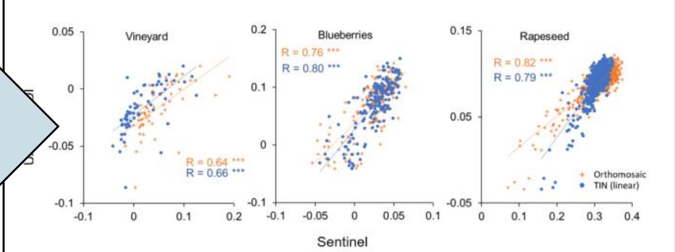
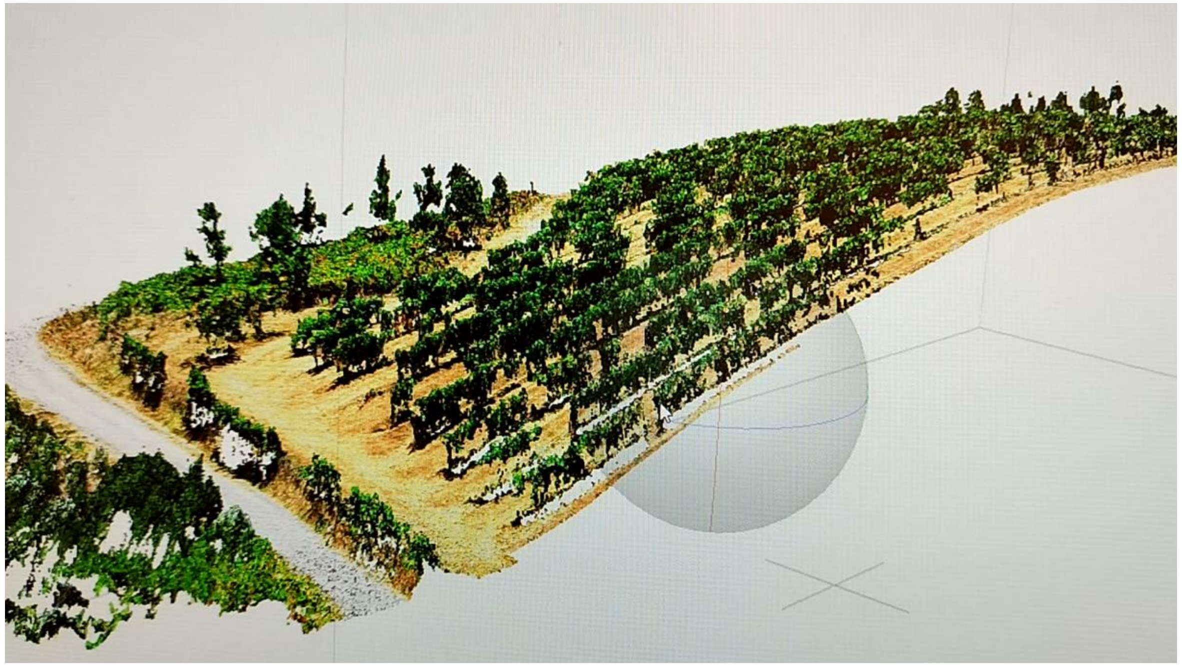
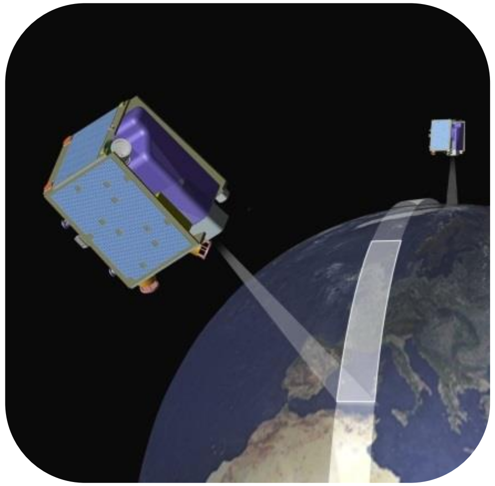


*Fig. 14. – Relationship between Sentinel 2 imagery and the UAV Vegetation Indices (NGRDI) generated using the Orthomosaic and the proposed methodology (TIN linear). Significance level: *p-value<0.05, **p-value<0.01, ***p-value<0.001.*

Detailed 3D models



How to obtain images?



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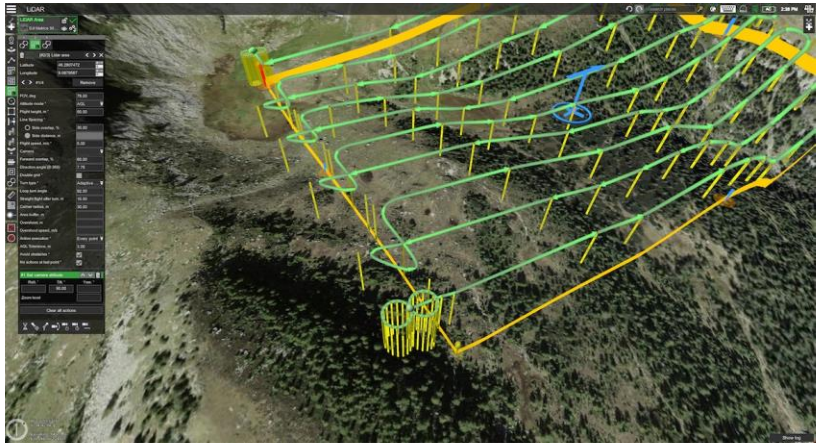
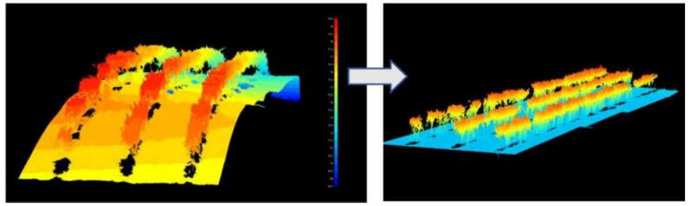
Drones flying close to the plants

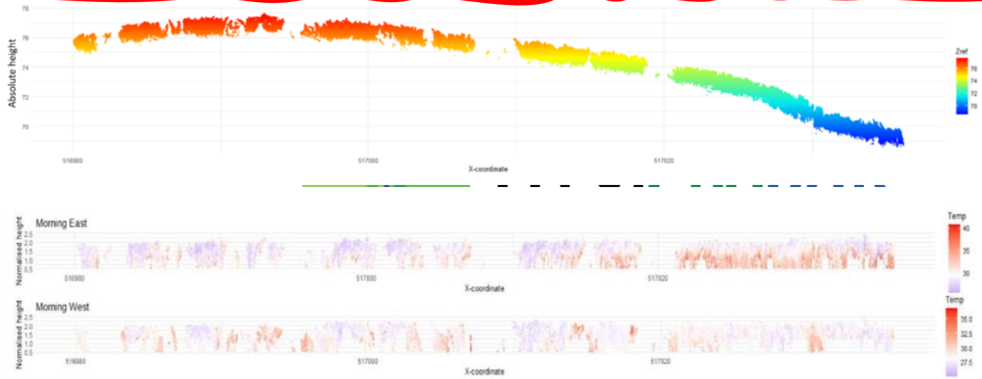


Ground robots moving close to the plants

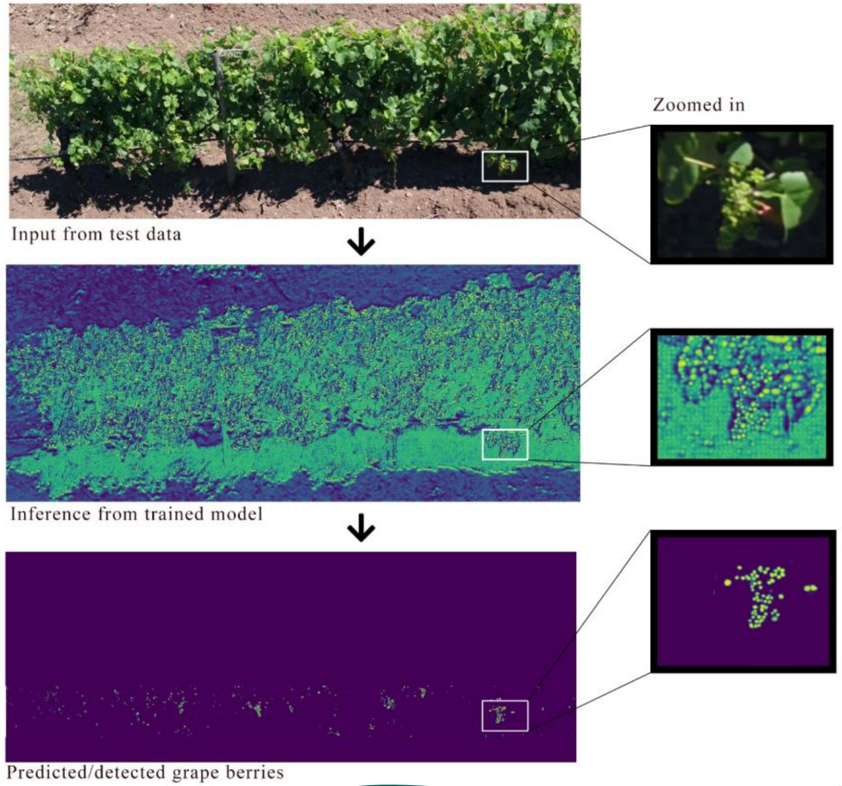
Very High-res approaches

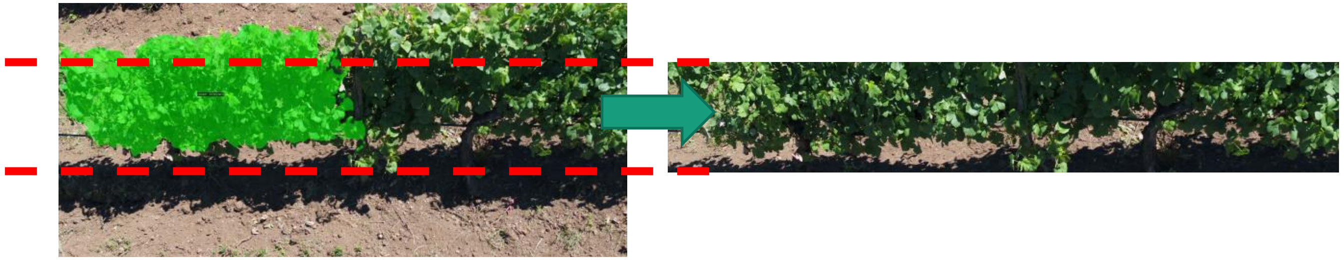
3D point clouds





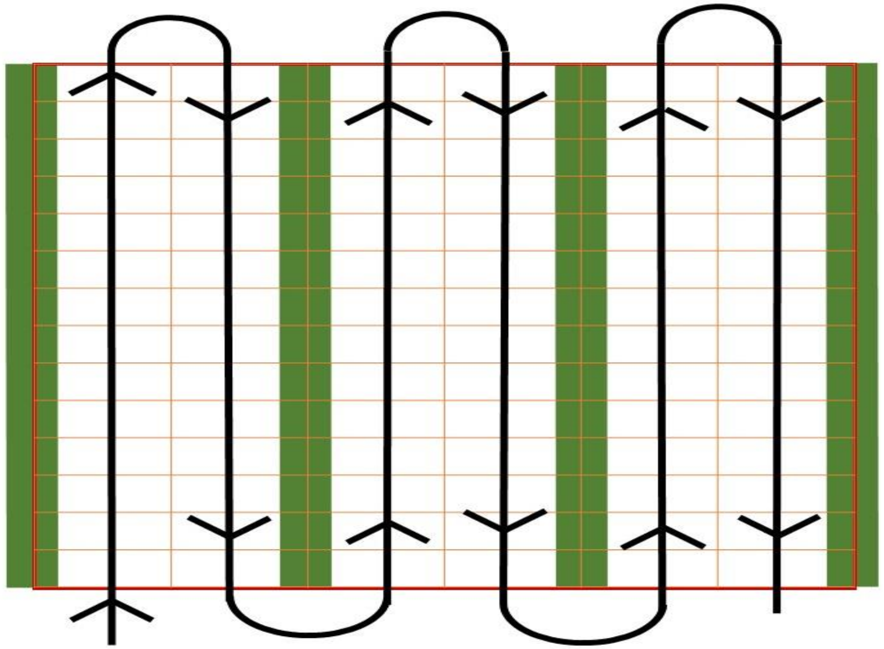
Improve fruit detection and tracking in (near) real-time





Fleet interoperability

XAG R150 | Treatment UGV



<u>Omnidirectional</u>

Movility in any direction

Example of a complete Precision Agriculture Workflow with Remote Sensing

FlexiGroBots - Flexible robots for intelligent automation of precision agriculture operations -

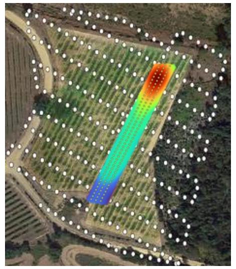
FLEXIGROBOTS

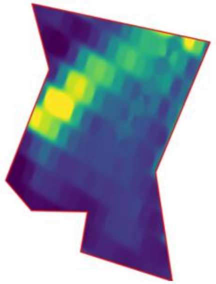
Test for the early detection of a disease affecting vineyards, Botrytis. Generation of a precise map of treatment

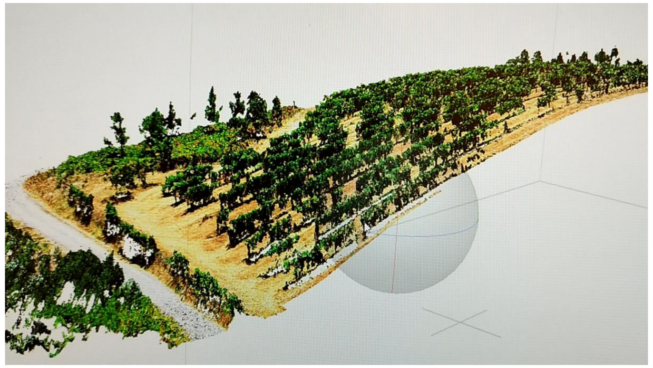
1. Geopositioning affected plants using a RTK GNSS system. Ground truth

UAV

2. UAV flights







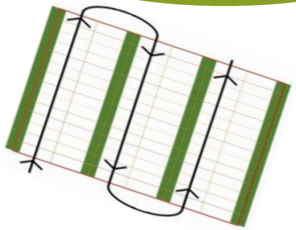
3. Assessment

4. Send the information to the UGV

UGV

5. The UGV scans the terrain following autonomously the UAVs probability map.

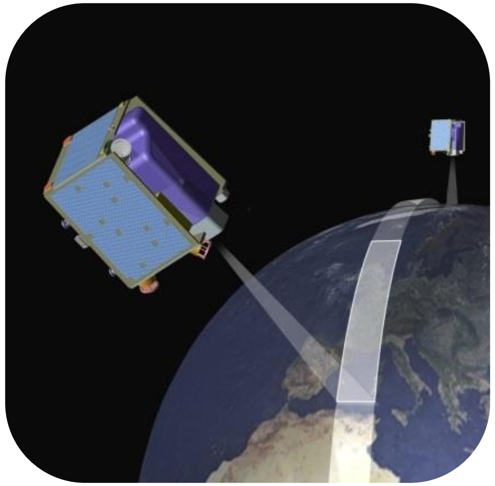
PLANNER



6. A map with the locations where Botrytis has been detected for treatment.

7. Analyse the accuracy of the generated map vs ground truth.

How to obtain images?



VS

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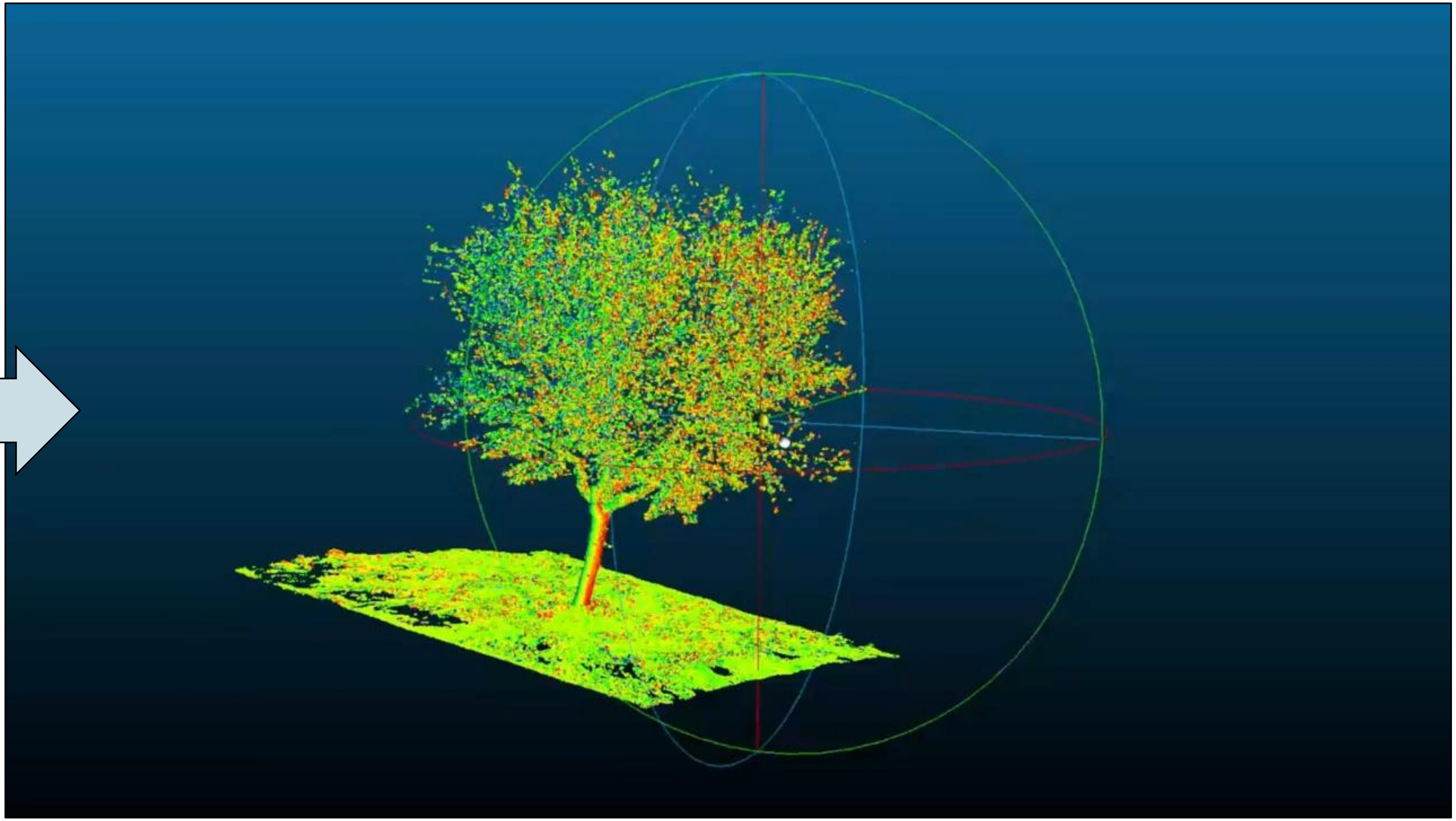
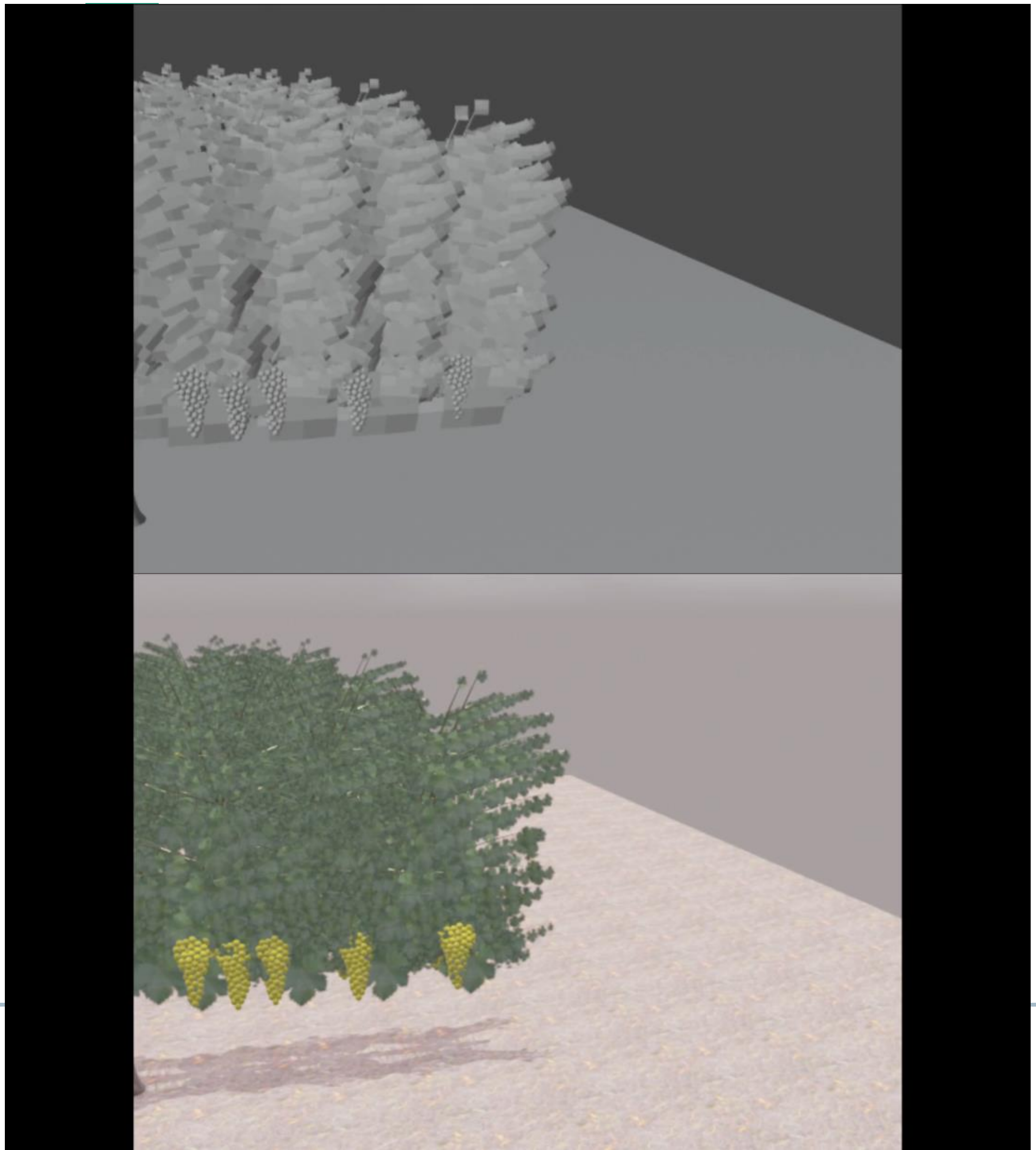
Fixed sensors

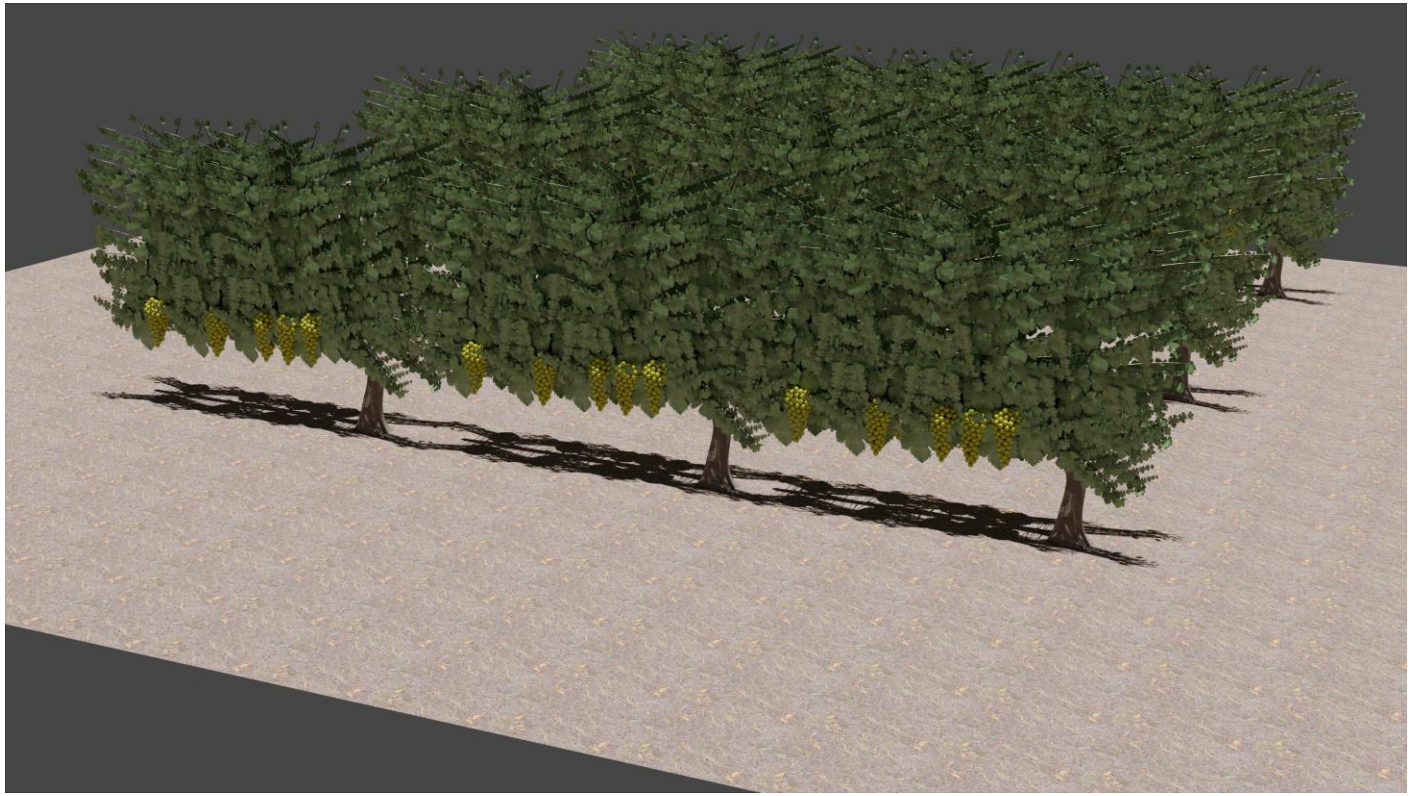
Not fixed sensors… handheld sensors or smartphones

Smartphones



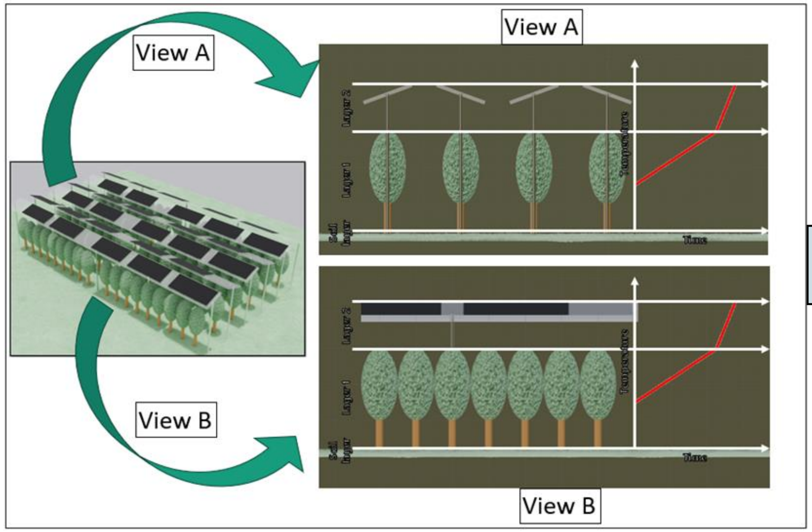
Remote Sensing with Synthetic Data – Digital Twins

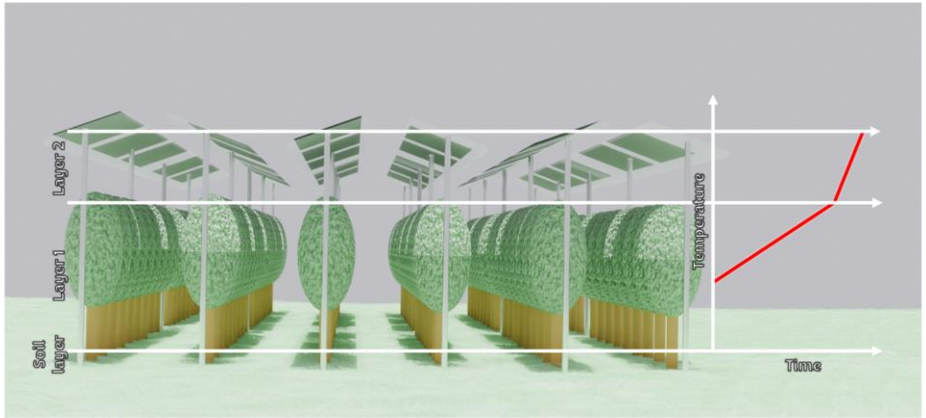


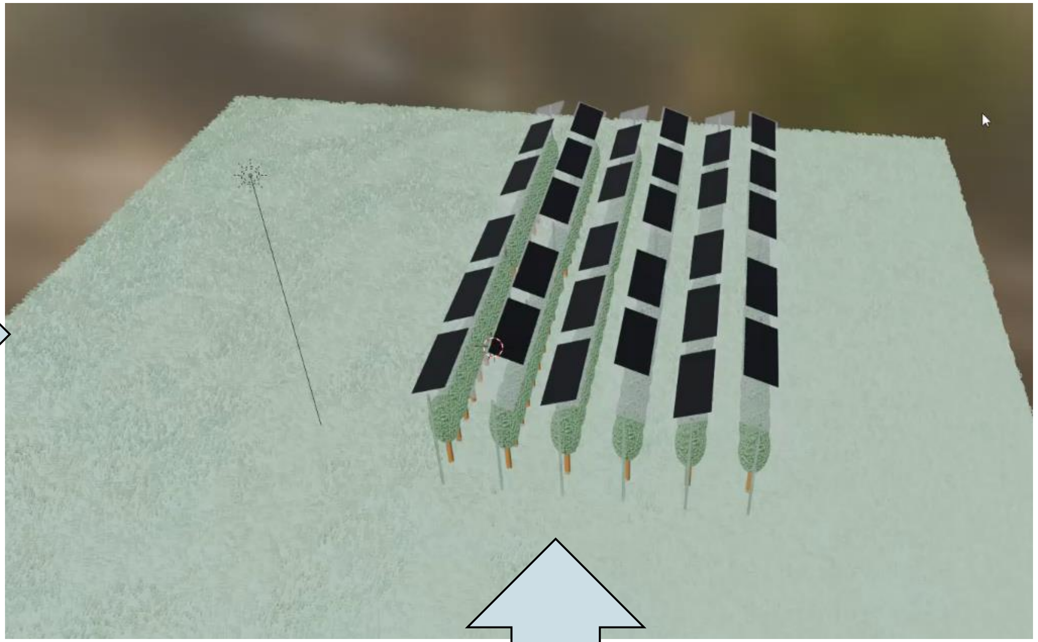


Microclimate

Assessing the Impact of Open Agrivoltaics on Microclimates by Modelling the Potential Heat Flux and Evapotranspiration







Agrivoltaics and Precision Agriculture

Remote Sensing in Agrivoltaics = Sum of RS in Photovoltaics and Agriculture?

The answer is NO

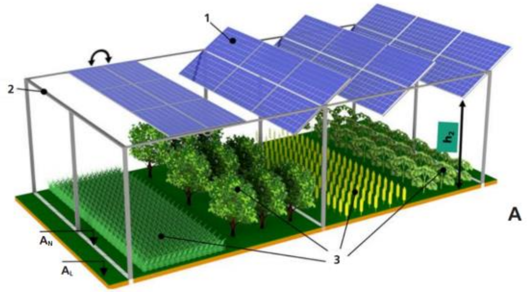
- **Reality:**
  - **Unique Challenges**
  - **Solar panels Structural Interference**
  - **Variable Lighting**
- **Integrated Approach**
  - **Advanced Algorithms**
  - **Customized Sensors**
  - **Holistic Monitoring**
- **Can we use the same techniques? partially**

vs

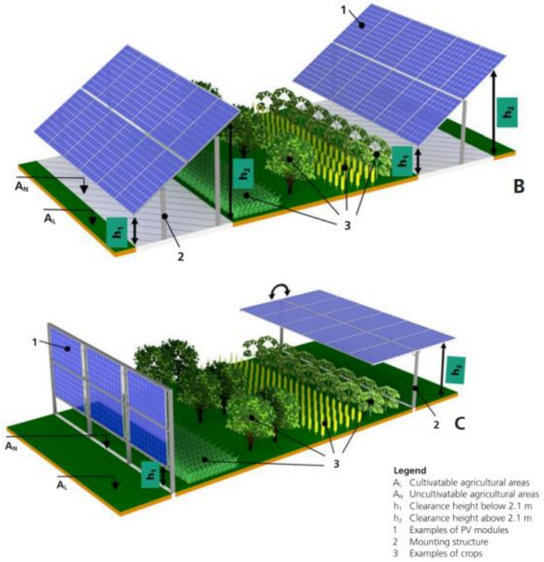
Figure 2. Left: Overhead agrivoltaic system with open sides, generating partial shade and solar electricity. Right: Greenhouse with semi-cylindrical roof and closed sides, with vents for climate control, adapted from (Akpenpuun et al., 2021).

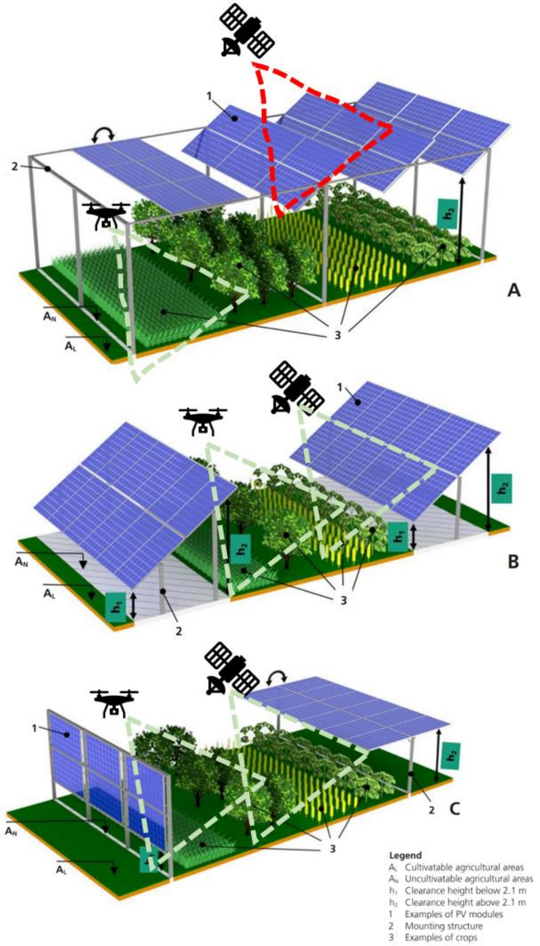
Issues with Each Configuration

Category I – Overhead PV



Category II – Interspace PV





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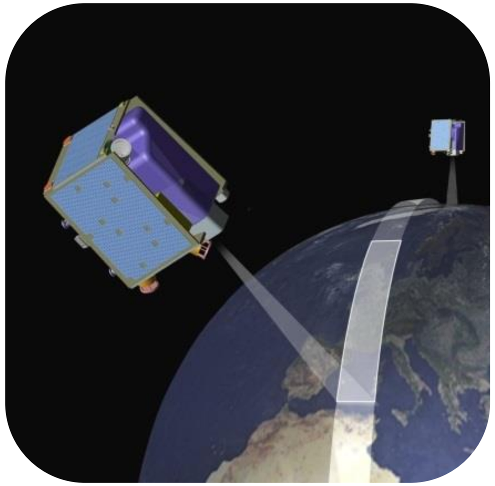

VS

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Case Study: Wellingen Category II – Interspace PV

Interspace agrivoltaics

No structural Obstructions:

- Solar panels and supports don’t block crop view.

Minor shadow Effects:

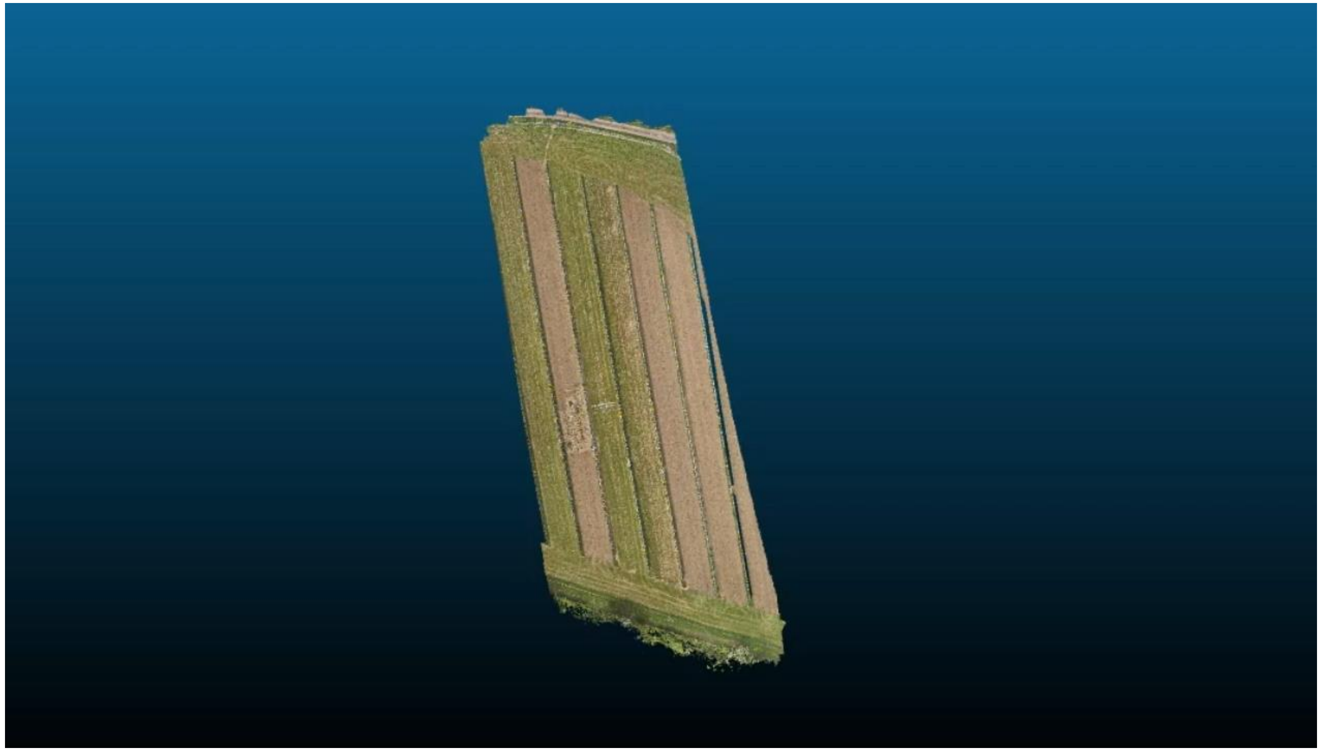
- Shadows from panels can affect data quality.

Data accuracy:

- Obstructions can cause data errors.

Good configuration:

- From a "remote sensing" point of view, the same data collection techniques used in precision agriculture can be employed.

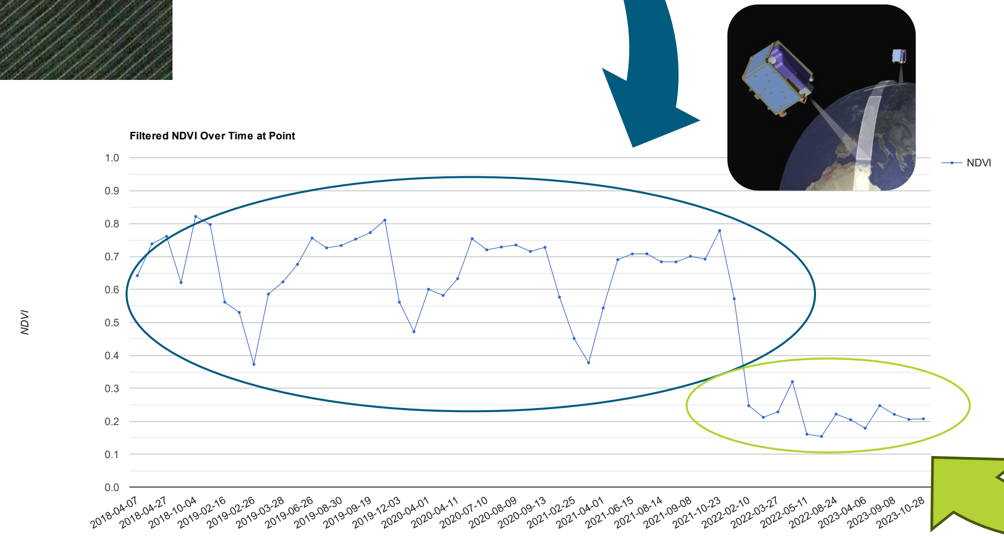


Case Study: Kressbronn Category I – Overhead PV

Overhead agrivoltaics

No Solar Panels until 2022

Current instalation of solar panels



NDVI evolution

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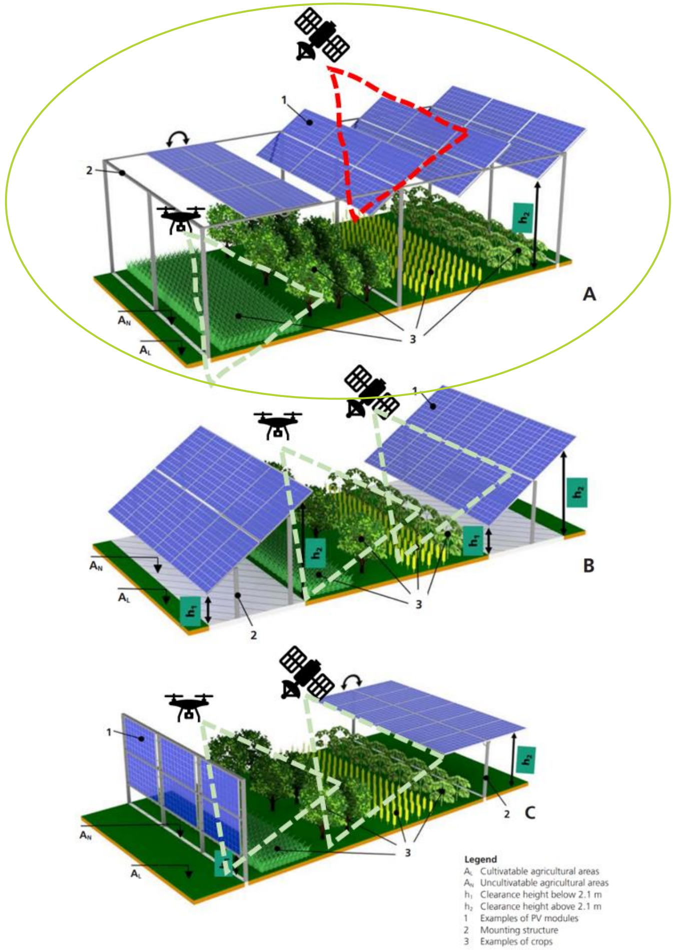
Case Study: Kressbronn Category I – Overhead PV

Overhead agrivoltaics



Case Study: Kressbronn Category I – Overhead PV

Overhead agrivoltaics

Structural Obstructions:

- Solar panels and supports block crop view.

Shadow Effects:

- Shadows from panels affect data quality.

Limited Angles:

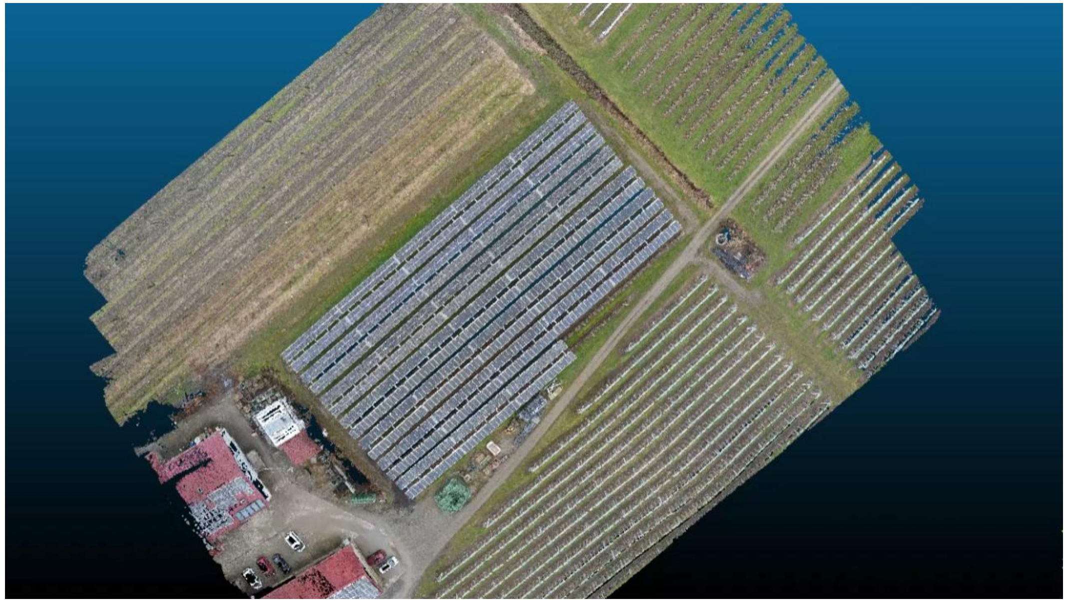
- Drones from above miss necessary oblique angles.

Data Inaccuracy:

- Obstructions and shadows cause data errors.

Possible solutions:

- Flexible flight paths for drones.
- Integrate data from ground-based sensors and other platforms.



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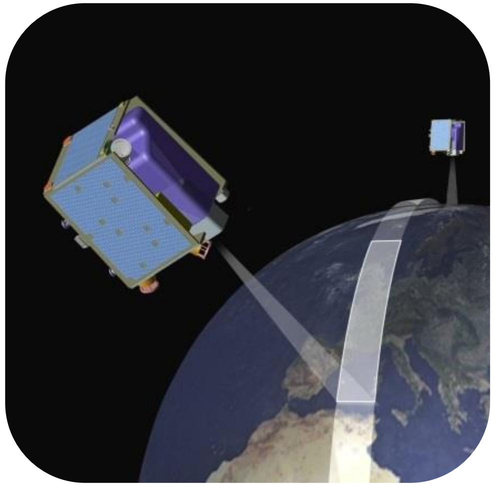

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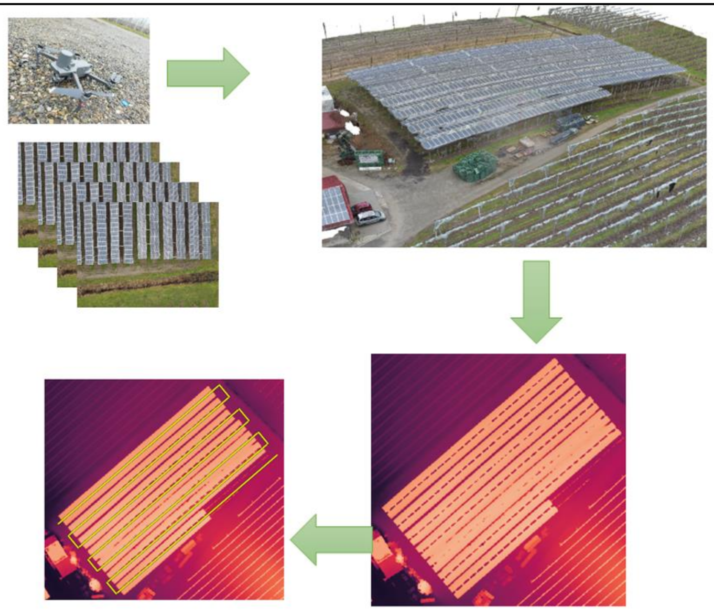
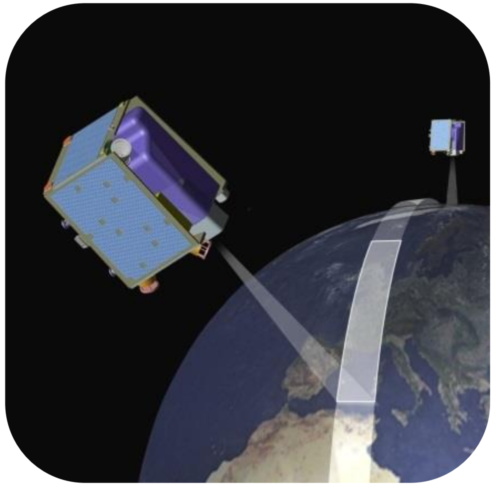


Figure 1. Optimized UAV Flight Path Strategy Considering Constraints in Overhead Agrivoltaic Systems. Yellow lines: UAV path.

How to obtain images?



VS

VS

Case Study: Kressbronn Category I – Overhead PV

Overhead agrivoltaics

Fly under the PV panels

Customized Flight Paths:

- The drone is flown between crop rows and beneath the solar panels, following a carefully planned path.

Shadow and Structural Challenges:

- Flying under the panels helps avoid issues with structural obstructions.

Data Collection Optimization:

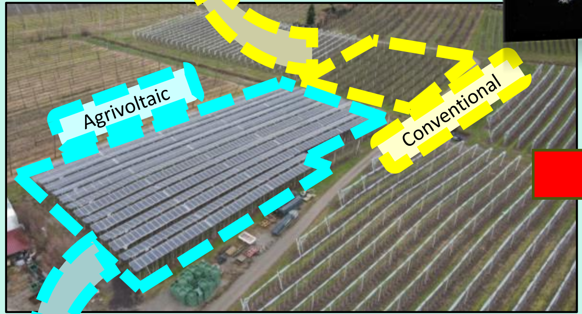
- By flying close to the crops with a tailored path, the drone gathers precise data on crop health and soil.

Agrivoltaic systems **improve land use and energy** production but may **interfere with GNSS signals** crucial for precision agriculture

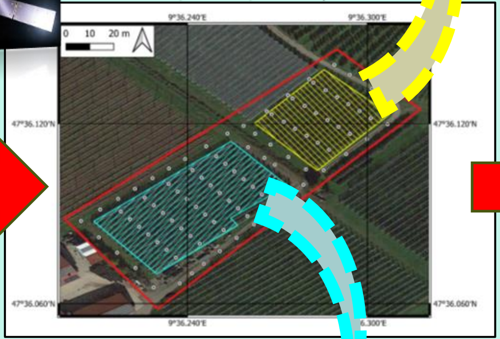
This research investigates **GNSS signal degradation** caused by agrivoltaic structures, focusing on signal strength and positional accuracy

Conventional

The study took place in two adjacent pome fruit orchards, one under an agrivoltaic system and one in an open-sky orchard



GNSS data was collected using a smartphone supporting multiple satellite constellations (GPS, GLONASS, Galileo, BeiDou)

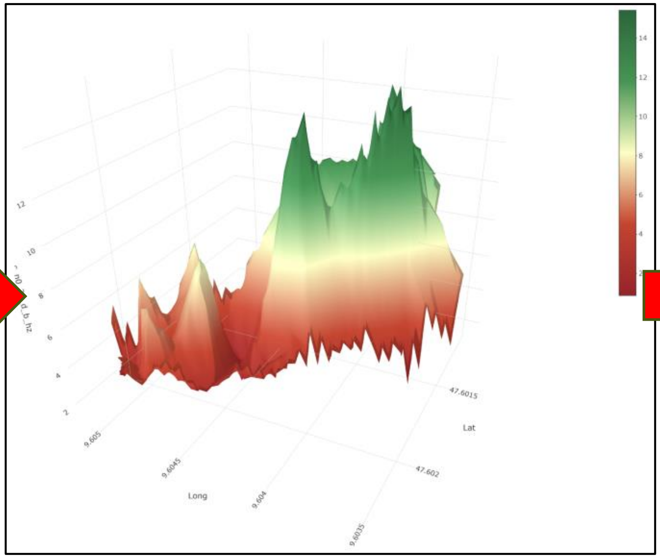


GNSS metrics like C/N_0, positional accuracy, and dilution of precision (DOP) were analyzed

Agrivoltaic

Data was processed to generate statistical insights and heatmaps showing GNSS performance differences

GNSS signal performance under the agrivoltaic system showed an average carrier-to-noise density ratio (C/N_0) of 26.92 dB-Hz, significantly lower than the 30.62 dB-Hz recorded in the conventional orchard



The number of satellites with C/N_0 values below 24 dB-Hz was notably higher in the agrivoltaic system (10.00 satellites on average) compared to 5.45 satellites in the conventional orchard, reflecting signal degradation

Despite the reduction in signal quality, the average number of satellites with usable signals (C/N_0 ≥ 24 dB-Hz) remained above 22 in both environments, ensuring basic GNSS functionality for precision agriculture

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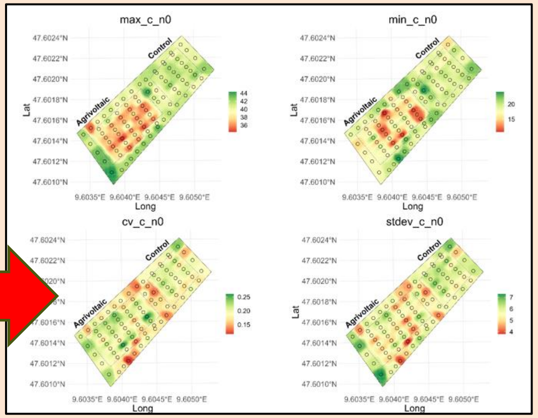
Overhead structures in agrivoltaic systems adversely affect GNSS signal quality



Multi-constellation GNSS receivers help mitigate signal degradation, ensuring enough satellites for reliable positioning

Technologies like RTK correction, post-processing software, or hybrid GNSS/IMU systems can improve precision under agrivoltaic panels

Further studies are needed on different agrivoltaic configurations and their effect on GNSS signals

Case Study: Kressbronn Category I – Overhead PV

Overhead agrivoltaics

Multi-Angle Data Collection:

- Essential for complete crop monitoring.
- Different camera views gather comprehensive data.

Benefits of Under-PV Flights:

- Detailed images of obscured crops.
- Captures crop health, soil conditions, and microclimate.

Multi-Camera Views:

- Nadir and oblique angles for thorough monitoring.
- Creating a Consistent Model:
  - Combines data from multiple angles.
  - Improves analysis and decision-making.

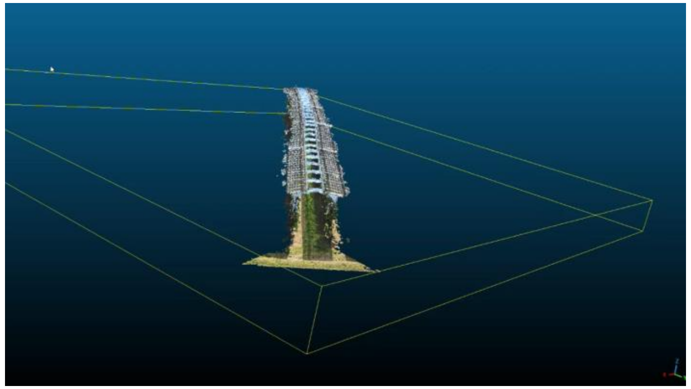
Case Study: Kressbronn Category I – Overhead PV

Overhead agrivoltaics

Final Objective:

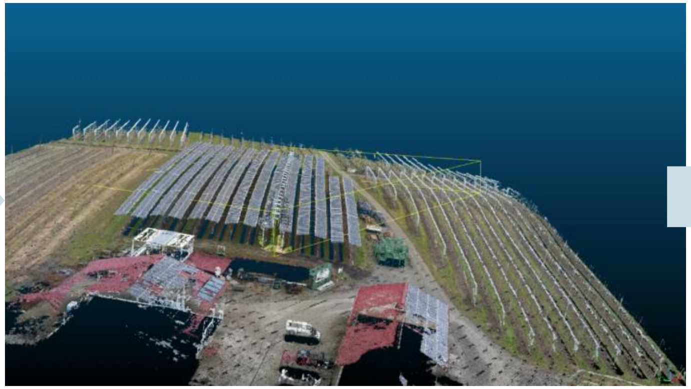
- Create a cohesive model
- Automated process

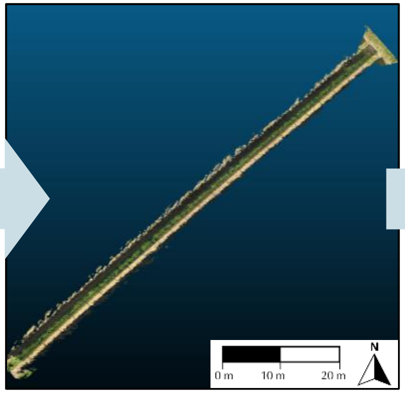
Model classification



Model segmentation

Orthomosaic generation





Prescription maps

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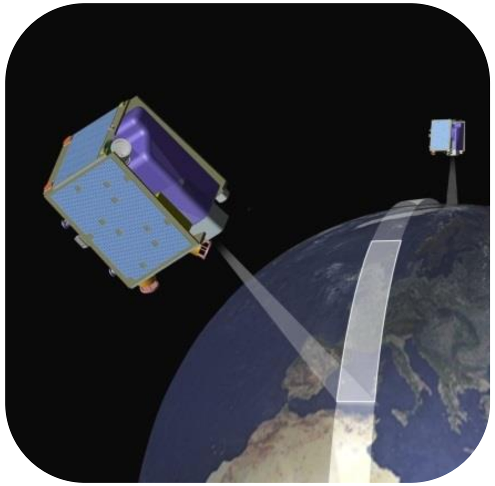
How to obtain images?

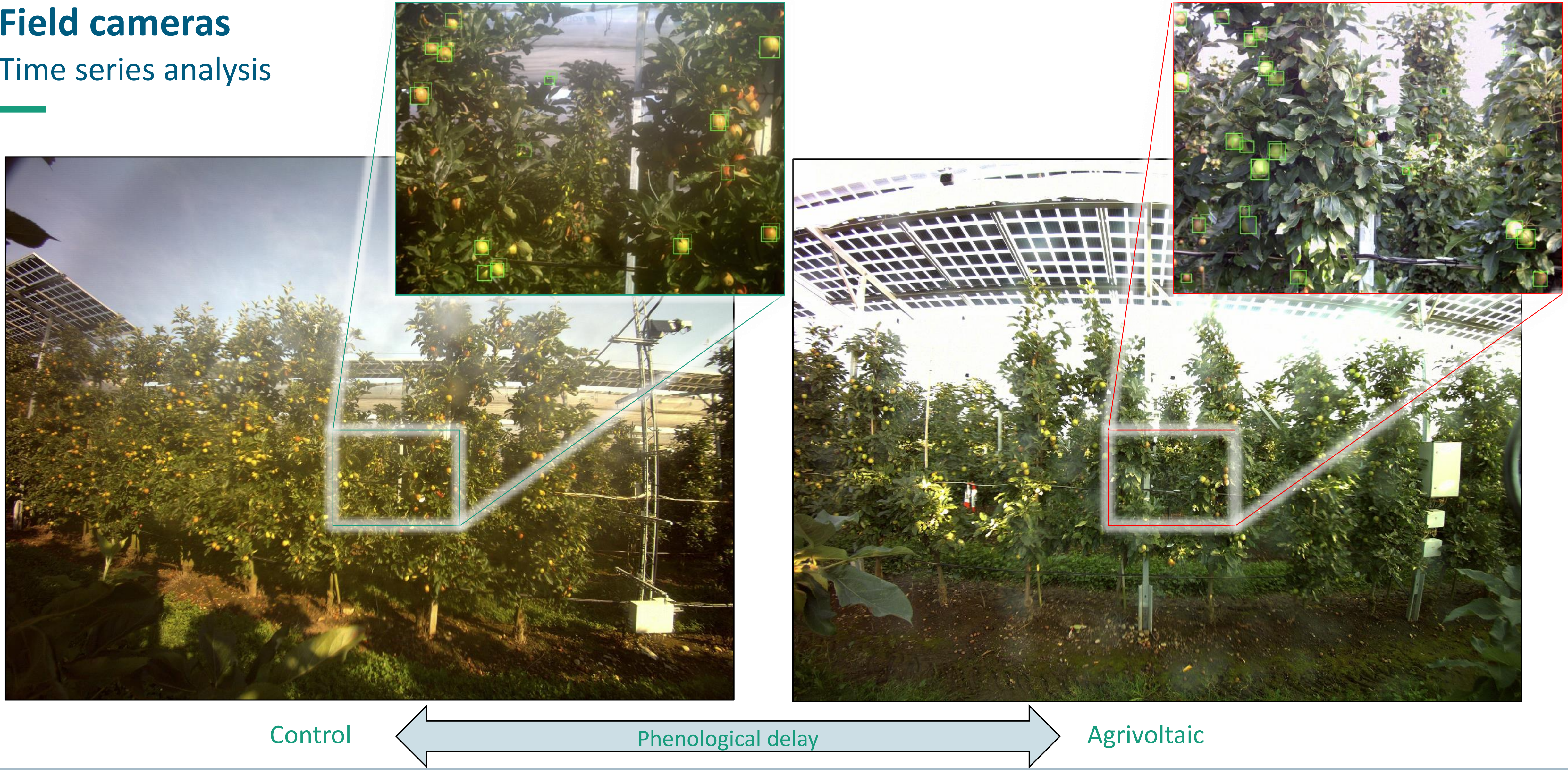


vs

vs

Field cameras

Time series analysis



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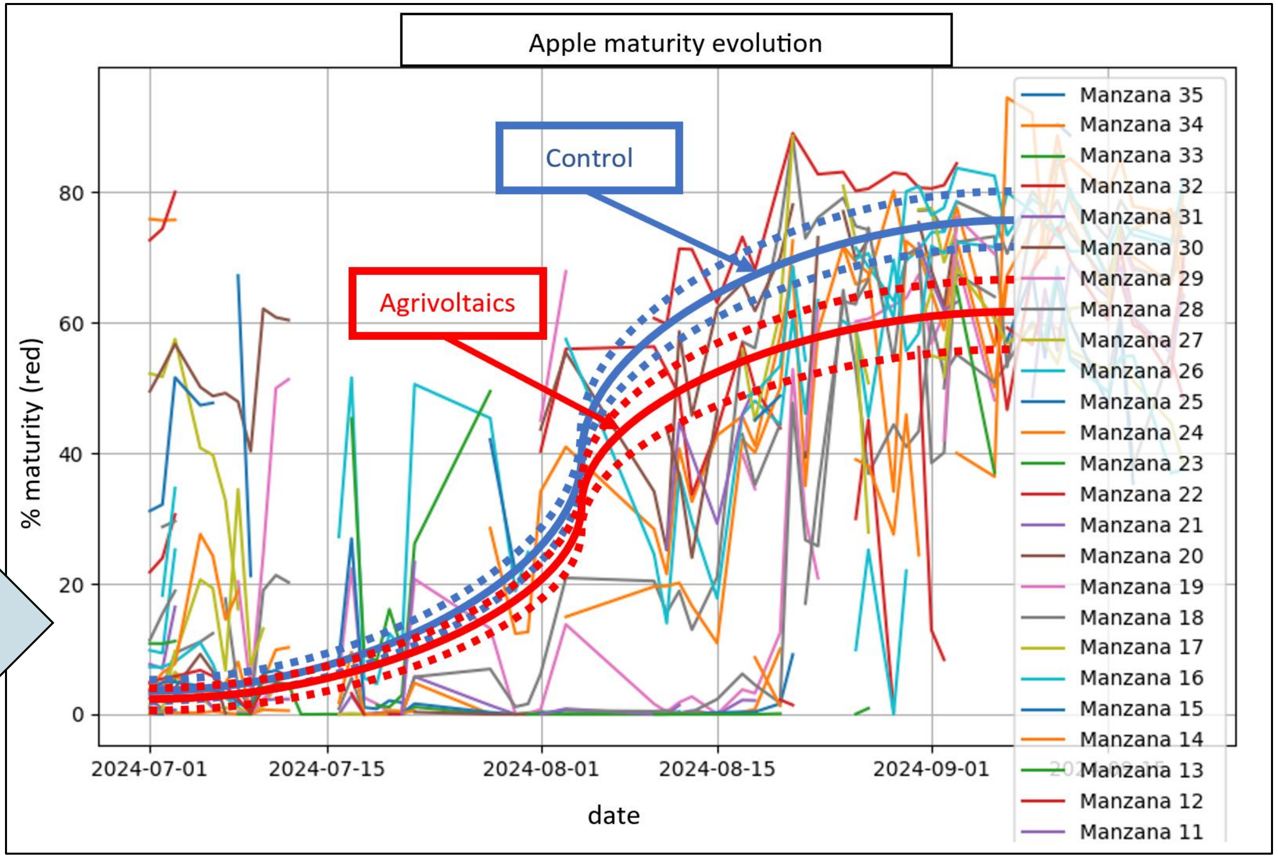
Field cameras

Time series analysis

Control — Phenological delay — Agrivoltaic

Field cameras

Time series analysis



Control — Phenological delay — Agrivoltaic

Field cameras

Time series analysis

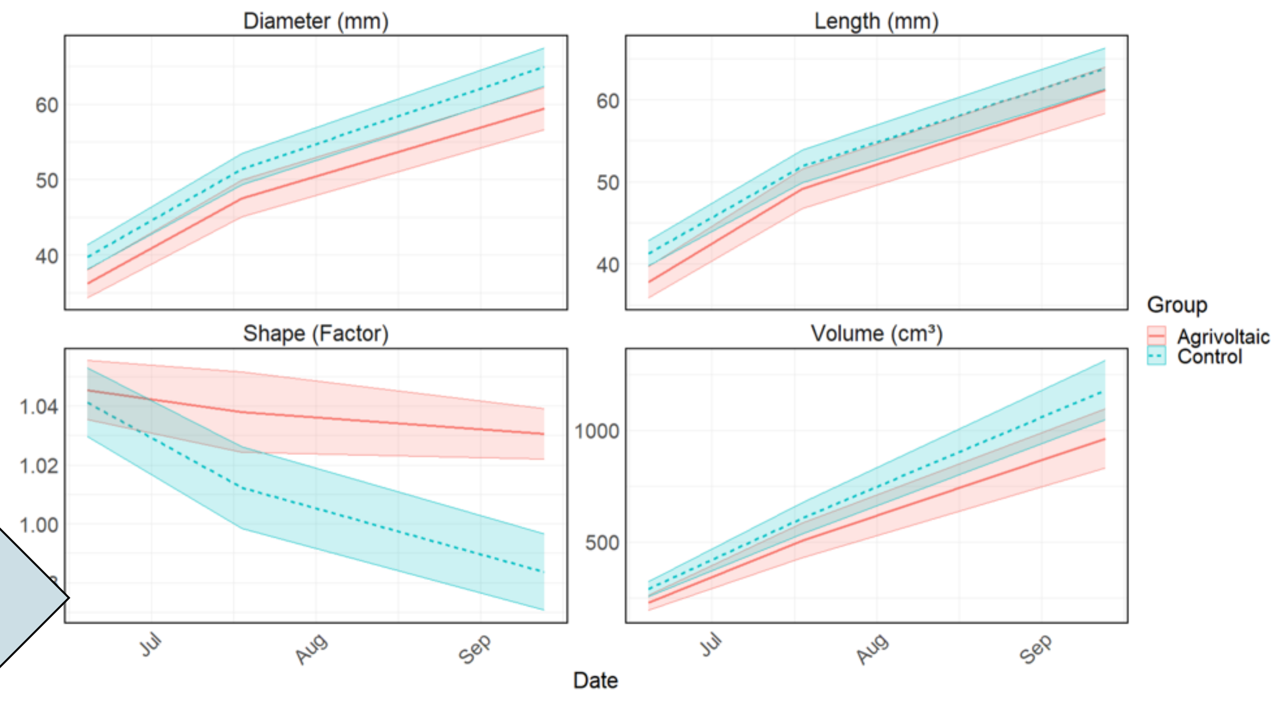


Figure 5. Temporal evolution of apple measurements (Diameter, Length, Shape, and Volume) for Agrivoltaic and Control groups over three time points. Each line represents the mean value, with shaded areas indicating the 95% confidence intervals for each group.

Control ⟷ Phenological delay ⟷ Agrivoltaic

Thank you for your kind attention

Contact

—

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