

Agriculture and solar photovoltaics: the promise of agrivoltaics for reducing land-use conflicts, enhancing food security, and combating climate change



Dr. Silvia Ma Lu
Department of Engineering Sciences
3rd September 2026
12.00 am – 1.00 pm

Acknowledgment of Country:
I acknowledge the Traditional Owners of the land on which we
meet today and pay my respects to Elders past and present.

Agenda

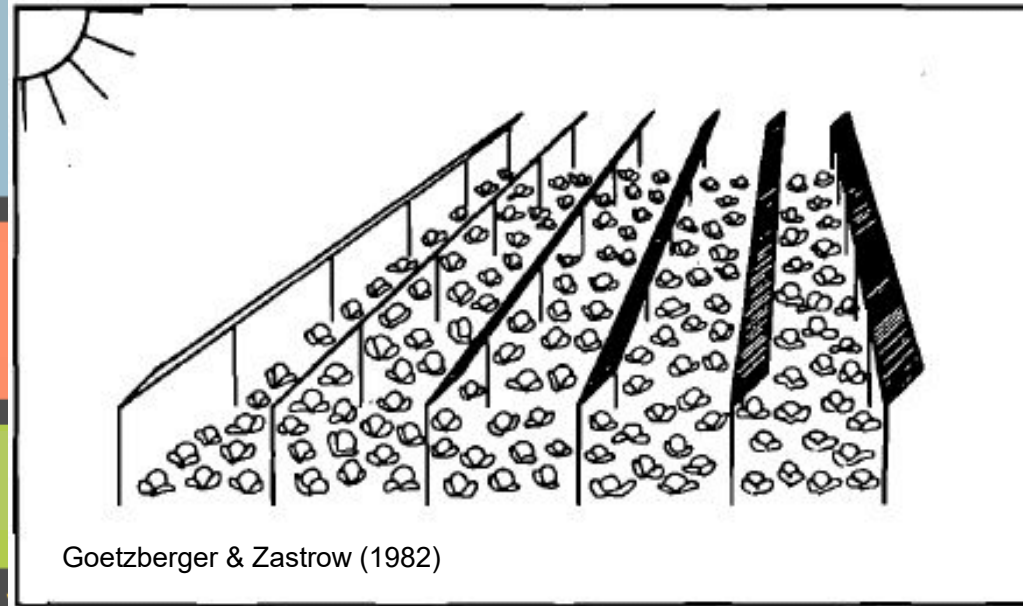
- Agrivoltaics 101
- Emerging spectrally-selective PV technologies for agrivoltaics
- Agrivoltaics research at Mälardalen University
- Agrivoltaics potential in the Australian context
- Discussion and Q&A



Agrivoltaics 101 – A promising concept

Climate change

- Extreme weather events



old – Paris Agreement)
l demand for water, energy and



w el c

c (PV)

- Fulfills several UN's Sustainable Development Goals
- From 14 GW_p worldwide in 2021 to 15 GW_p Europe alone in 2025⁴

1. IEA (2021), Net Zero by 2050, IEA.

2. IRENA (2019). Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (a global energy transformation: Paper).

3. Goetzberger & Zastrow (1982). On the coexistence of solar-energy conversion and plant cultivation. Int. J. Sol. Energy. 1(1), 55-69.

4. Masson et al. (2025). Trends in PV Applications 2025, IEA.

Agrivoltaics 101 – Classification



Proposed by Fraunhofer ISE. Adapted from Gorjian et al. (2022). Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology. Renew. Sustain. Energy Rev. 158, 112126. Source: Ma Lu et al. (2024). Wavelength-selective solar photovoltaics systems to enhance the spectral sharing of sunlight in agrivoltaics. Joule, 8, 2483–2522.

Agrivoltaics 101 – An interdisciplinary field

- ✓ Reduce land-use conflicts
- ✓ Increase food and energy security
- ✓ Fight climate change

670
Data
Portal
Entries



Data Portal
(NLR)

324 Physical

305 Microclimate

In summary, we need more DEMONSTRATIONS to:

- Show the feasibility across sites and climates
- Calibrate and validate models
- Understand underlying mechanisms
- Set standards and regulations

BUT other challenges appear:

- Time-consuming, weather-dependent
- Scale and transferability

- ? Does it always benefit agricultural yield?
- ? Does it work everywhere?
- ? Any negative impacts?

- × Site-, climate-, crop-, system design-dependent
- × Microclimate effects
- × Standards and integrated modelling

52 Social Perspectives

116 Market Assessments

47 Policy & Regulatory

159 Economics

36 Standards & Best Practices

115 Impact Assessments

38 Tools

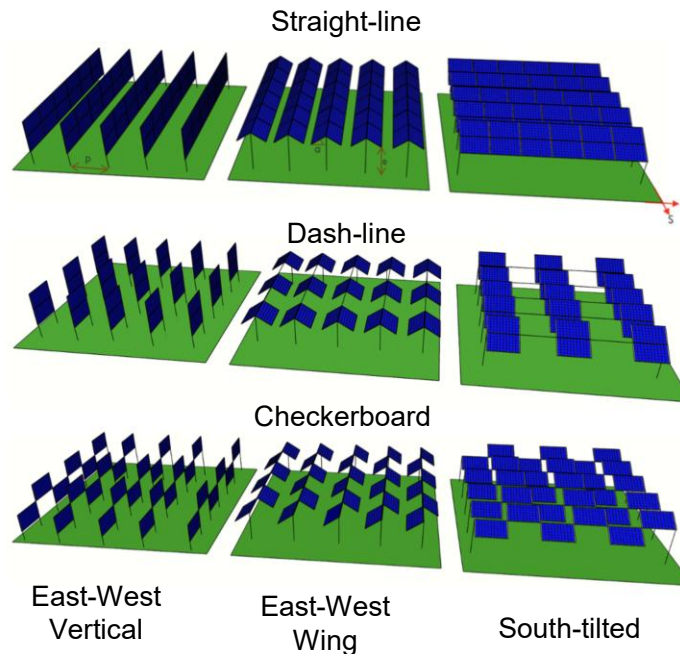
14 Methodological Comparisons

184 Reviews / Informational

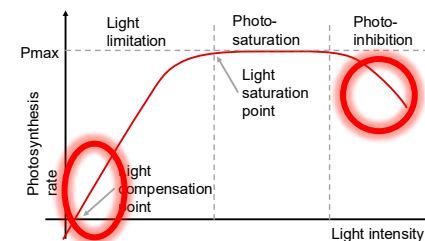
Emerging research directions

- Excessive high light intensity can harm plant growth by causing photo-inhibition¹.
- Severe shading is generally detrimental to plant growth².

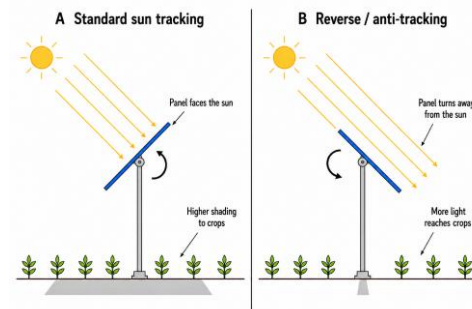
Spatial optimization



Light-response curve



Tracking strategies



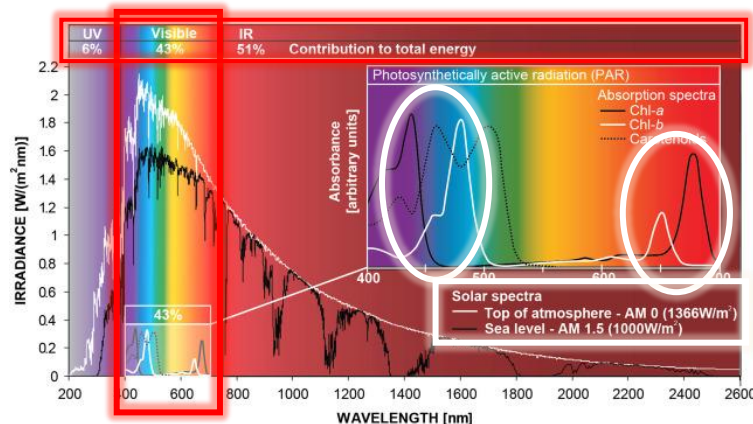
1. Baker (1996). "Photoinhibition of Photosynthesis," in Light as an Energy Source and Information Carrier in Plant Physiology, eds R. C. Jennings, G. Zucchelli, F. Ghetti, and G. Colombetti (New York, NY: Plenum Press), 89–97.

2. Touil et al. (2021). Shading effect of photovoltaic panels on horticulture crops production: a mini review. Rev. Environ. Sci. Biotechnol. 20, 281–296.

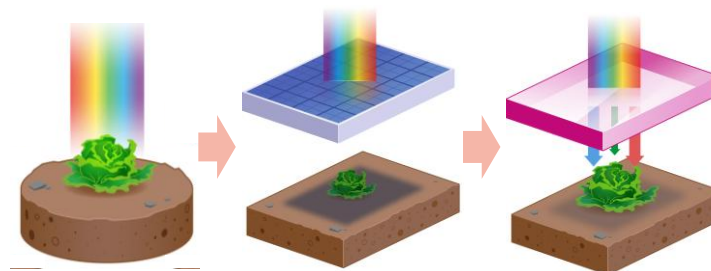
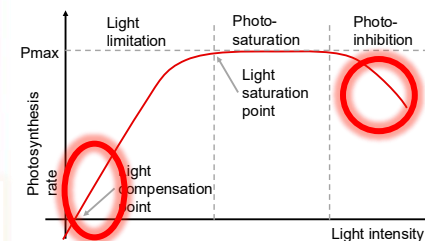
Asa'a et al. (2025). Evaluating the influence of different agrivoltaic topologies on PV energy, crop yields and land productivity in a temperate climate. Renewable Energy, 252, 123528

Emerging spectrally-selective PV technologies for agrivoltaics

- Excessive high light intensity can harm plant growth by causing photo-inhibition¹.
- Severe shading is generally detrimental to plant growth².
- Plants require a specific spectrum of solar irradiance to perform photosynthesis and grow³: photosynthetically active radiation (PAR).



Light-response curve



From optimizing light quantity to both quantity & quality

Wavelength-selective solar photovoltaic (WSPV) technologies consider the absorption profiles of plants and enable the transmission of light at wavelengths that are beneficial for photosynthesis.⁴

1. Baker (1996). "Photoinhibition of Photosynthesis," in Light as an Energy Source and Information Carrier in Plant Physiology, eds R. C. Jennings, G. Zucchini, F. Ghatti, and G. Colombetti (New York, NY: Plenum Press), 89–97.

2. Touil et al. (2021). Shading effect of photovoltaic panels on horticulture crops production: a mini review. Rev. Environ. Sci. Biotechnol. 20, 281–296.

3. Zhen et al. (2021). Why Far-Red Photons Should Be Included in the Definition of Photosynthetic Photons and the Measurement of Horticultural Fixture Efficacy. Front. Plant Sci. 12:693445.

4. Shi et al. (2019). Spectral engineering of semitransparent polymer solar cells for greenhouse applications.

Ringsmuth et al. (2016). Can photosynthesis enable a global transition from fossil fuels to solar fuels, to mitigate climate change and fuel-supply limitations? Renew. Sustain. Energy Rev., 62, 134–163.

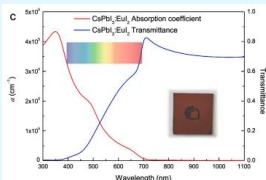
Ma Lu et al. (2024). Wavelength-selective solar photovoltaic systems to enhance the spectral sharing of sunlight in agrivoltaics. Joule, 8 (9), 2483–2522.

Emerging spectrally-selective PV technologies for agrivoltaics

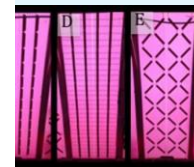
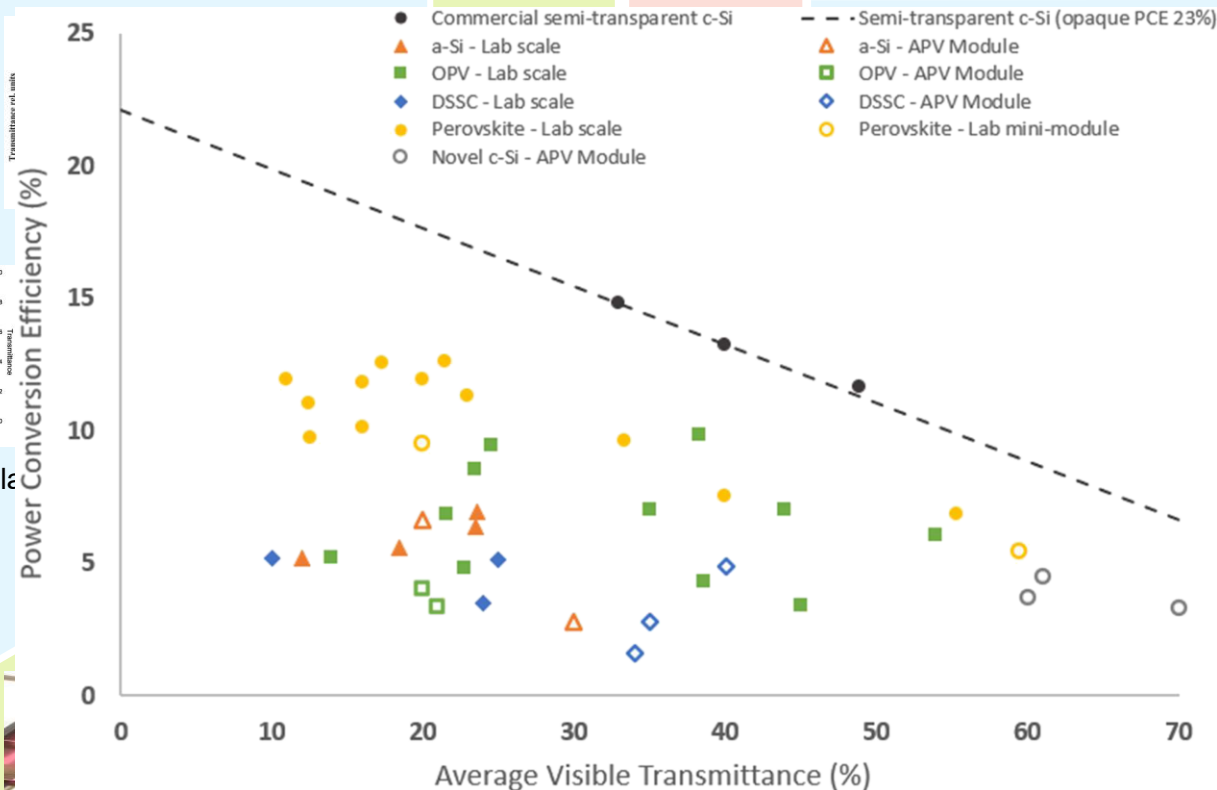
Organic PV



Perovskites



Dye-sensitized solar



Agrivoltaics research at Mälardalen University (Sweden) since 2021

Site's weather station:

- GHI, DHI
- PAR and PAR diffuse
- Air temperature
- Wind speed, direction
- Precipitation
- Relative humidity

Kärro Prästgård (59.55°N, 16.76°E)

Other sensors:

- Albedometers
- NDVI
- Soil moisture and temperature
- Micro-lysimeters
- PAR

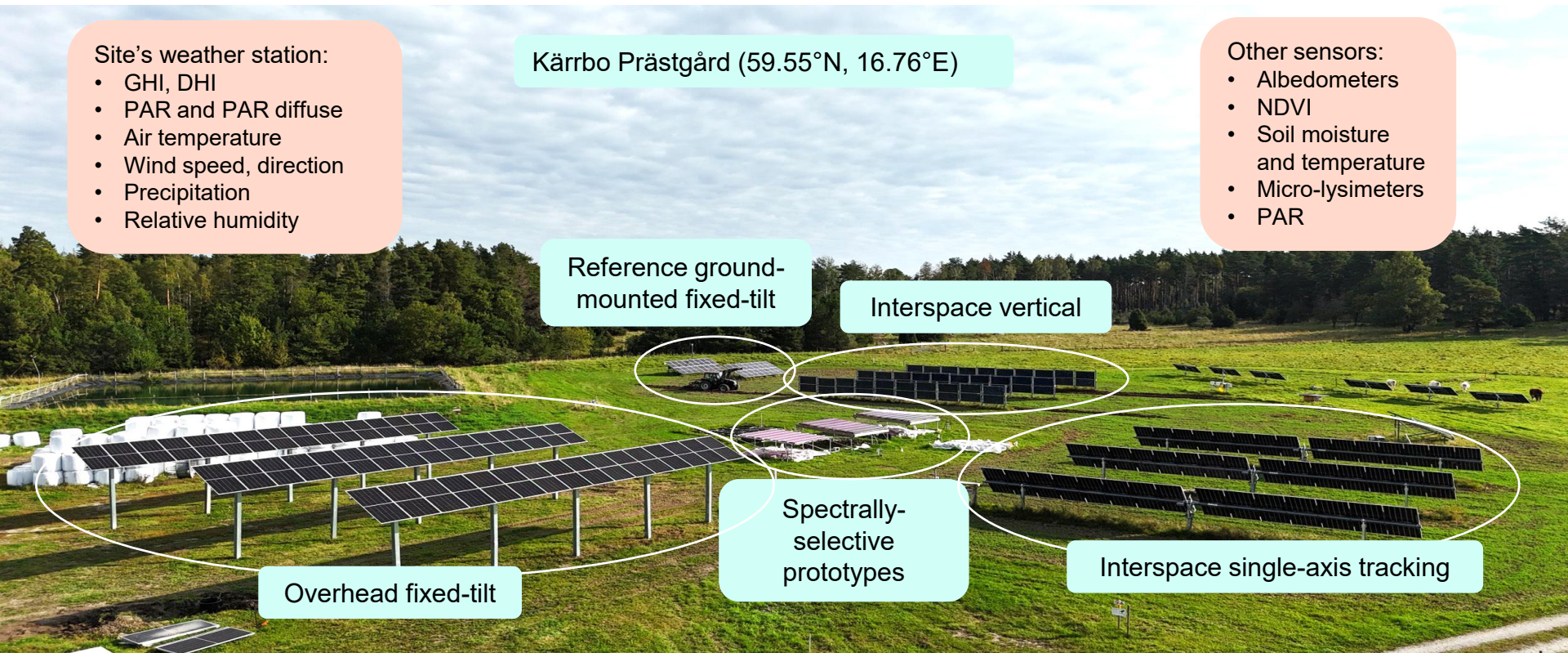
Reference ground-mounted fixed-tilt

Interspace vertical

Spectrally-selective prototypes

Overhead fixed-tilt

Interspace single-axis tracking



Other sites in Sweden where we have access to do research



Interspace vertical – Solvallen, Fellingsbro >600 kWp (59.47°N, 15.52°E)

Different row distances: 8m, 10m, 12m



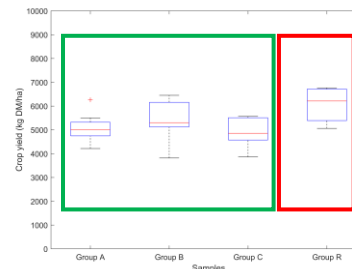
Interspace single-axis tracking – Hova, 6 MWp (58.85°N, 14.20°E)

Row distance: 16m

Some results from our vertical agrivoltaic systems



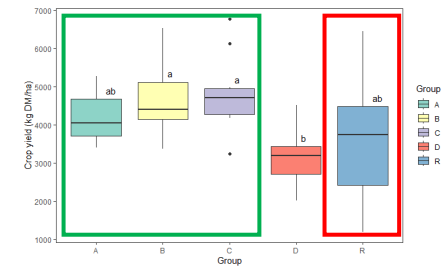
**Ley grass
2021-2022**



Agrivoltaic

Control

Barley 2023



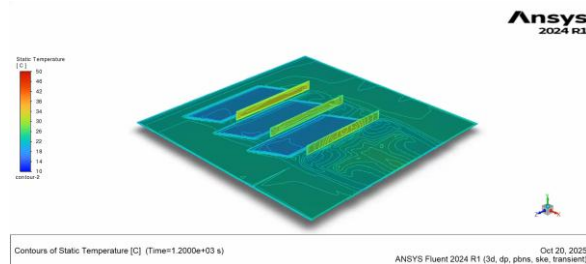
No statistically significant difference between crop yield under the vertical agrivoltaic system compared to open field conditions

Oats 2024: No statistically significant difference

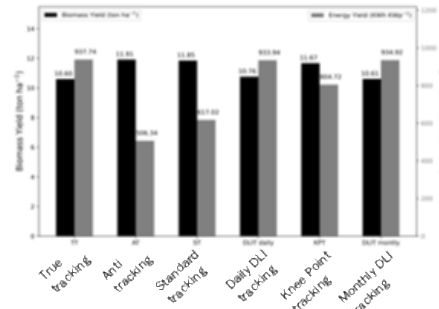
Oats 2025: No statistically significant difference (except East side)

But, 10% of land unused due to the structure of the solar modules → 90% of the yield per area

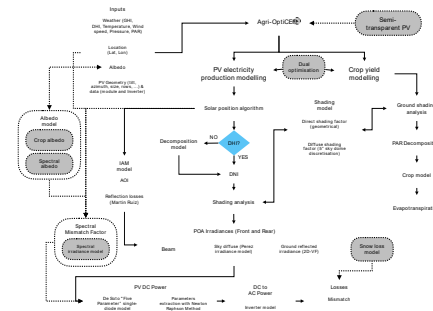
Agrivoltaics research at Mälardalen University



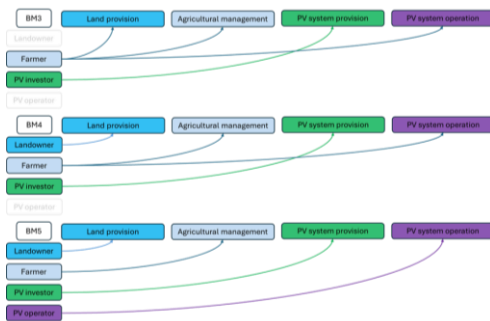
CFD – Microclimate modelling



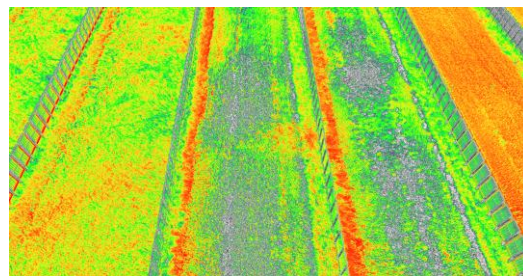
Tracking strategies



Integrated modelling, simulation and optimization



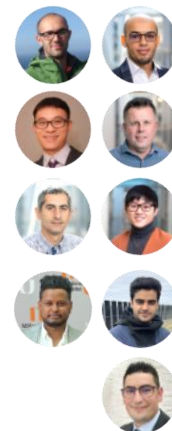
Economy and Business Models



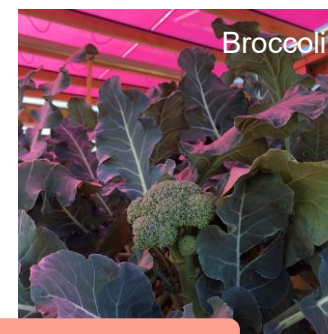
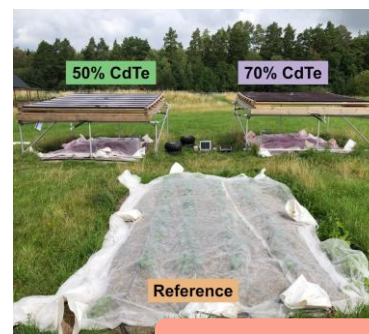
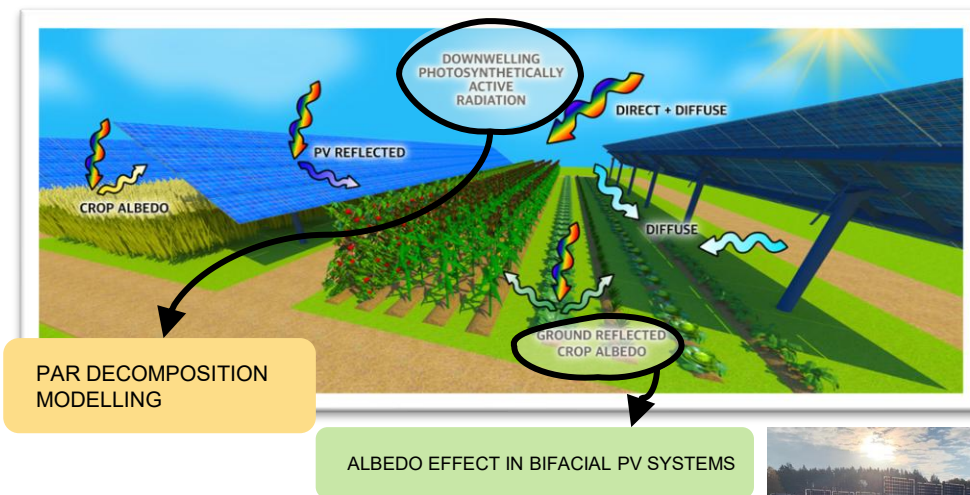
Crop performance and health



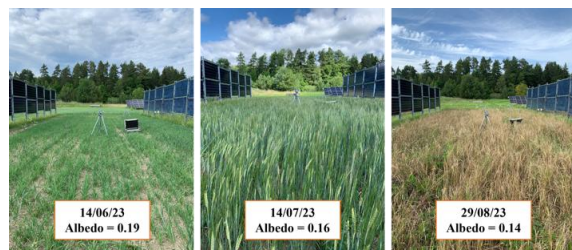
Aesthetics, landscape integration



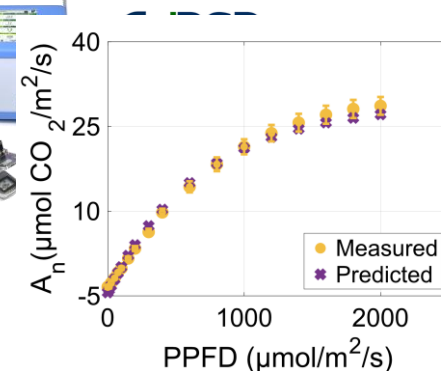
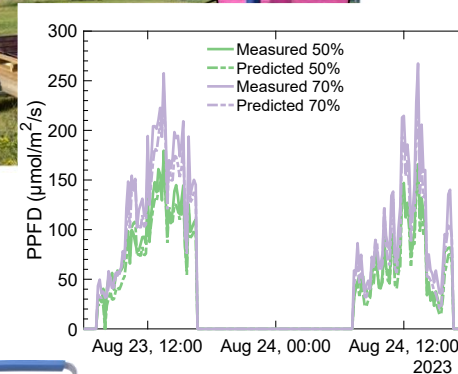
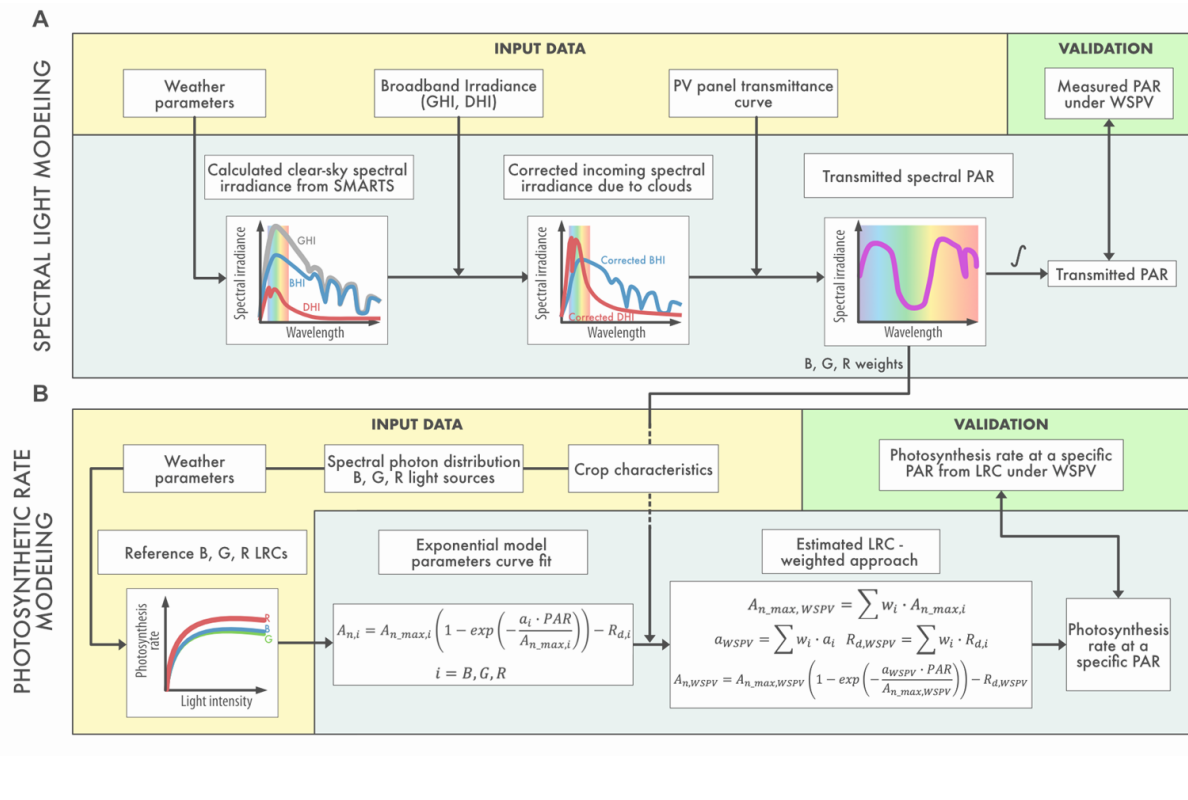
Solar irradiance components and field experiments under WSPVs



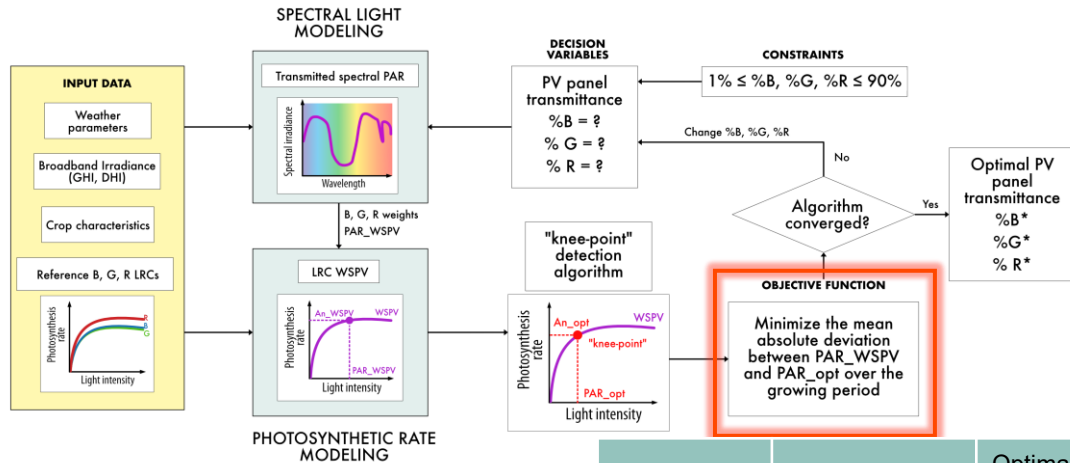
Delay in reaching maturity



Modelling wavelength-selective agrivoltaics



A single-objective optimization problem



What is the optimal percentage of **BLUE** (%B), **GREEN** (%G) and **RED** (%R) light transmittance that a WSPV technology should have for a specific location and crop (broccoli)?

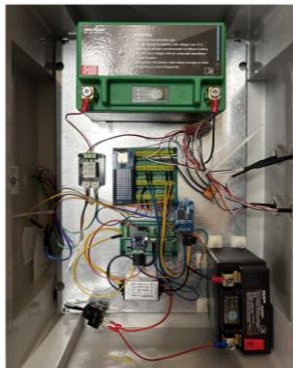
*knee-point = trade-off point between photosynthetic rate and light intensity

Location	Growing period (fall harvest)	Optimal % transmitted light per region from sunlight			Avg %T	Mean DLI sunlight (mol m ⁻² d ⁻¹)	Mean DLI under WSPV (mol m ⁻² d ⁻¹)
		%B	%G	%R			
Freiburg	15 Jul – 30 Sep	78	1	90	56.33	32.24	18.49
Gobi	1 Aug – 15 Oct	90	9	46	48.33	40.64	21.31
Kyoto	1 Sep – 15 Nov	89	1	90	60.00	29.29	17.72
Montpellier	1 Sep – 15 Nov	90	1	88	59.67	28.31	17.10
Oulu	15 Jun – 30 Aug	90	23	90	67.67	38.33	26.23
Phoenix	1 Oct – 15 Dec	90	2	90	60.67	30.47	18.29
Stockholm	1 Jul – 15 Sep	90	1	85	58.67	39.53	23.96

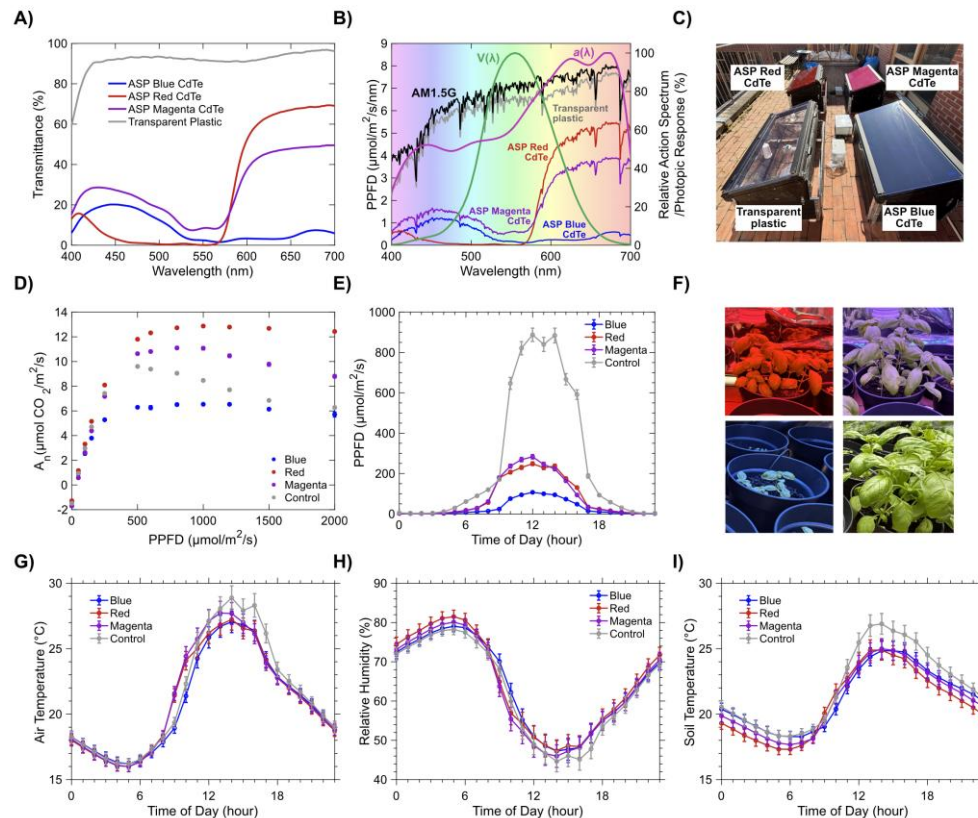
Further research on spectrally-selective PVs

Semi-transparent blue, red, and magenta thin-film PV modules in agrivoltaics:
Insights from basil cultivation

+ Info at EU PVSEC 2026
Thu Sep 17, 5.00 – 6.30 pm
Session 4DO.5



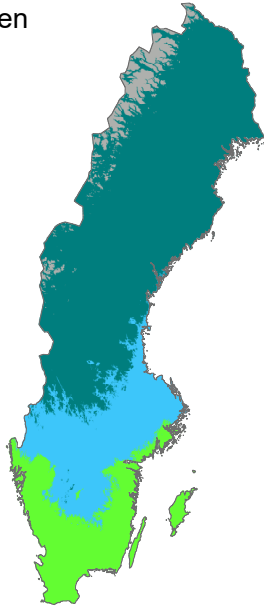
Low-cost IoT monitoring system



Unpublished results

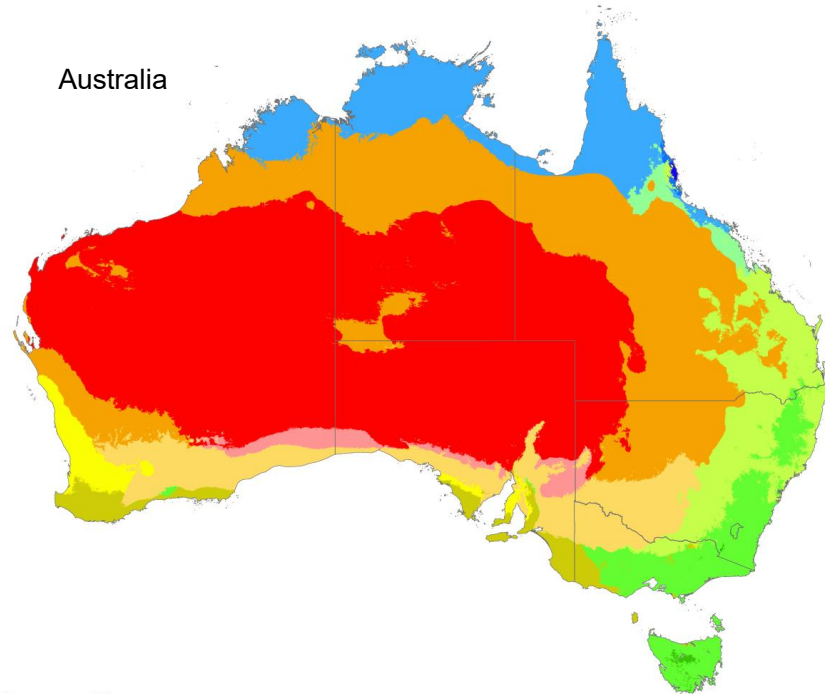
Agrivoltaics potential in the Australian context

Sweden



Limited
transferability of
results

Australia



Köppen climate type

- ET (Tundra)
- Dfb (Warm-summer humid continental)
- Dfc (Subarctic)
- Cfb (Oceanic)

*Isotherm used to separate temperate (C) and continental (D) climates is -3°C
Data source: Climate types calculated from data from WorldClim.org

Not to scale

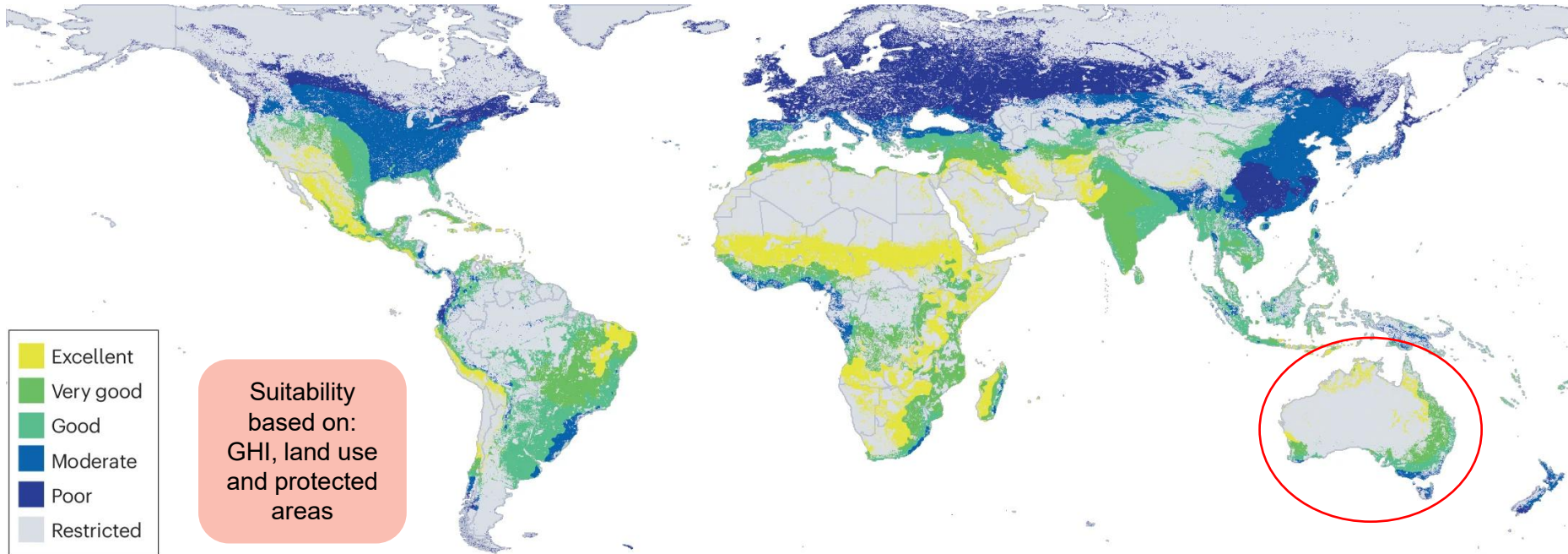
Adam Peterson (2016), CC BY-SA 4.0, via Wikimedia Commons

Köppen climate type

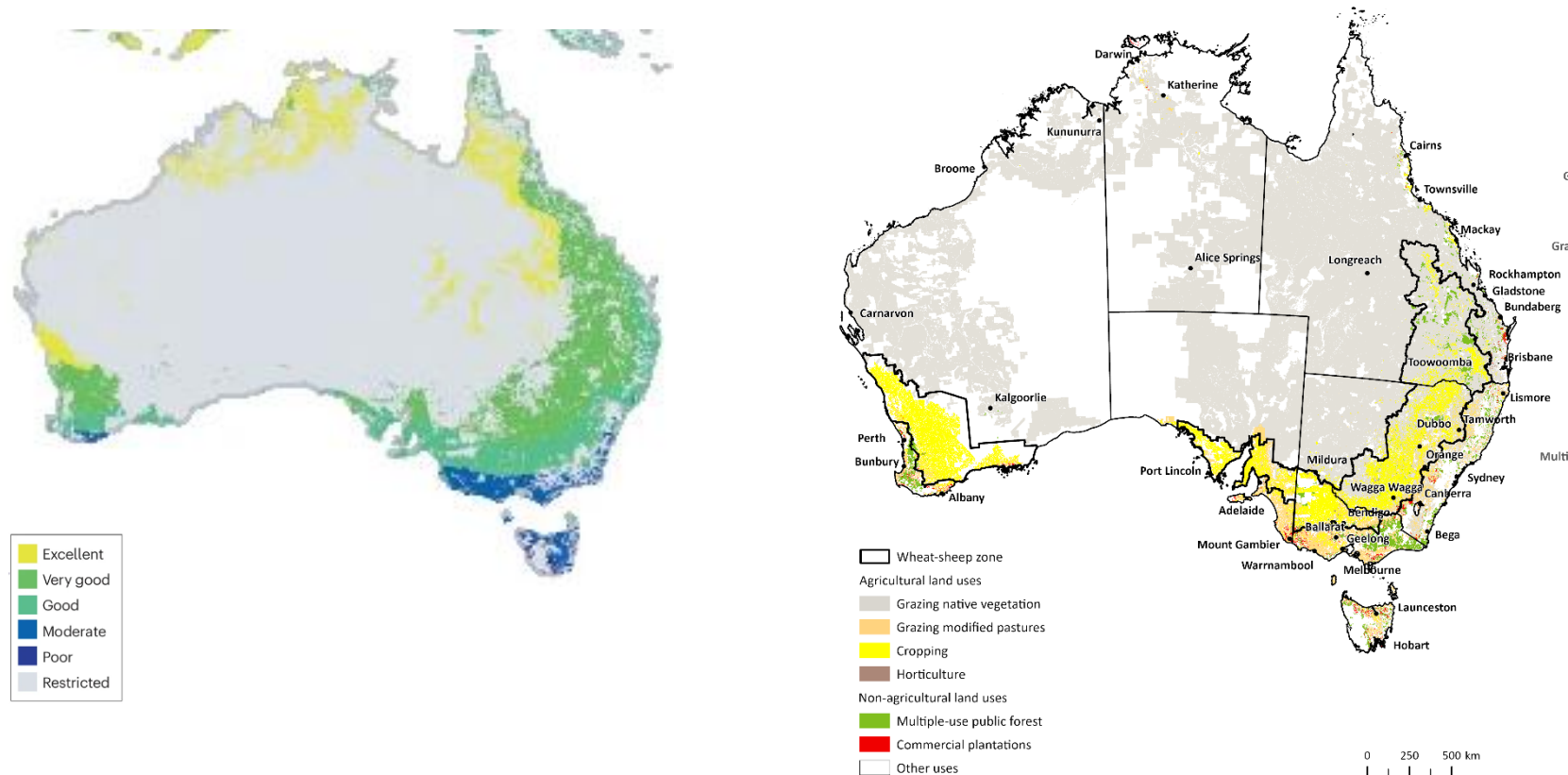
- ET (Tundra)
- Dfb (Subarctic)
- Cfc (Subpolar oceanic)
- Cfb (Oceanic)
- Cfa (Humid subtropical)
- Cwa (Humid subtropical)
- Csb (Warm-summer mediterranean)
- Csa (Hot-summer mediterranean)
- BSk (Cold semi-arid)
- BSh (Hot semi-arid)
- BWk (Cold desert)
- BWh (Hot desert)
- Aw (Savanna)
- Am (Monsoon)
- Af (Rainforest)

*Isotherm used to separate temperate (C) and continental (D) climates is -3°C
Data source: Climate types calculated from data from WorldClim.org

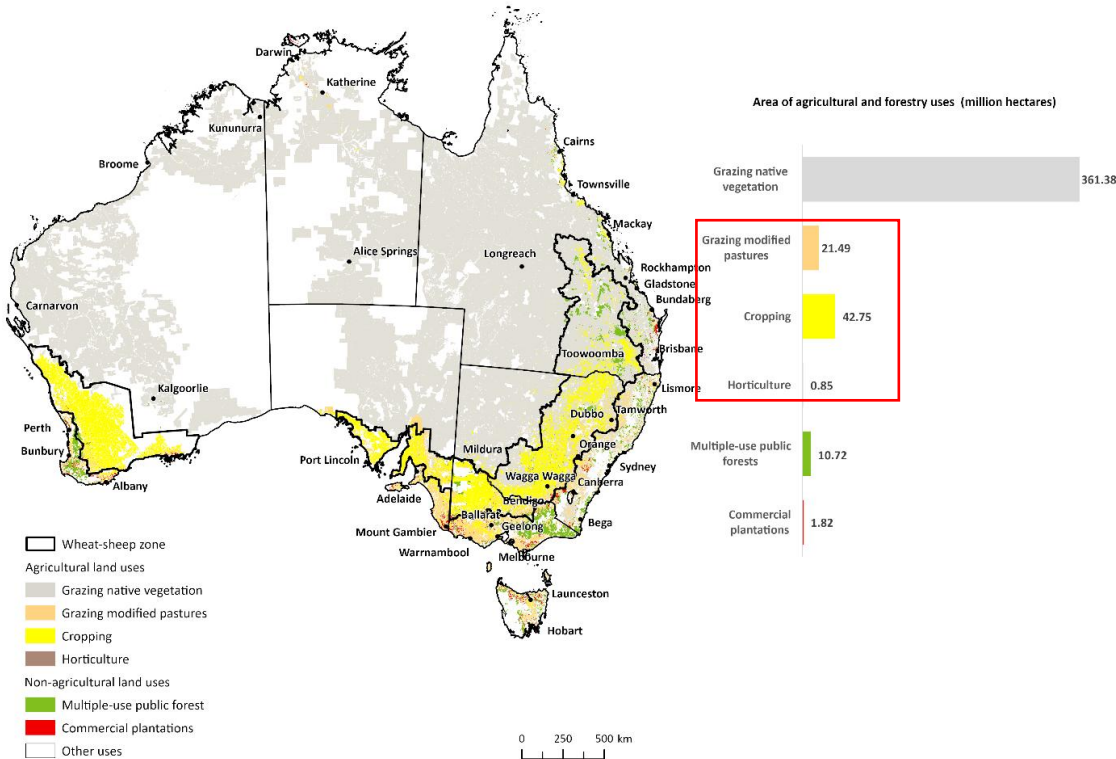
Agrivoltaics potential in the Australian context



Agrivoltaics potential in the Australian context



Agrivoltaics potential in the Australian context



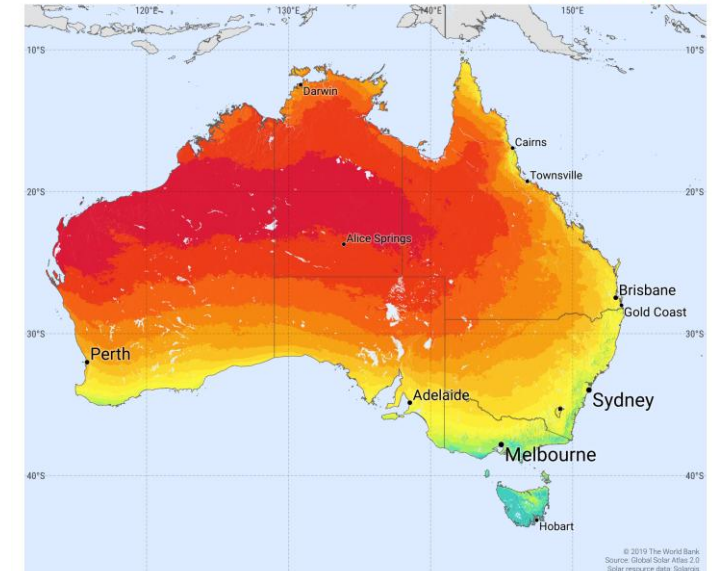
Assumed flat PV

SOLAR RESOURCE MAP

GLOBAL HORIZONTAL IRRADIATION AUSTRALIA



ESMAP SOLARGIS

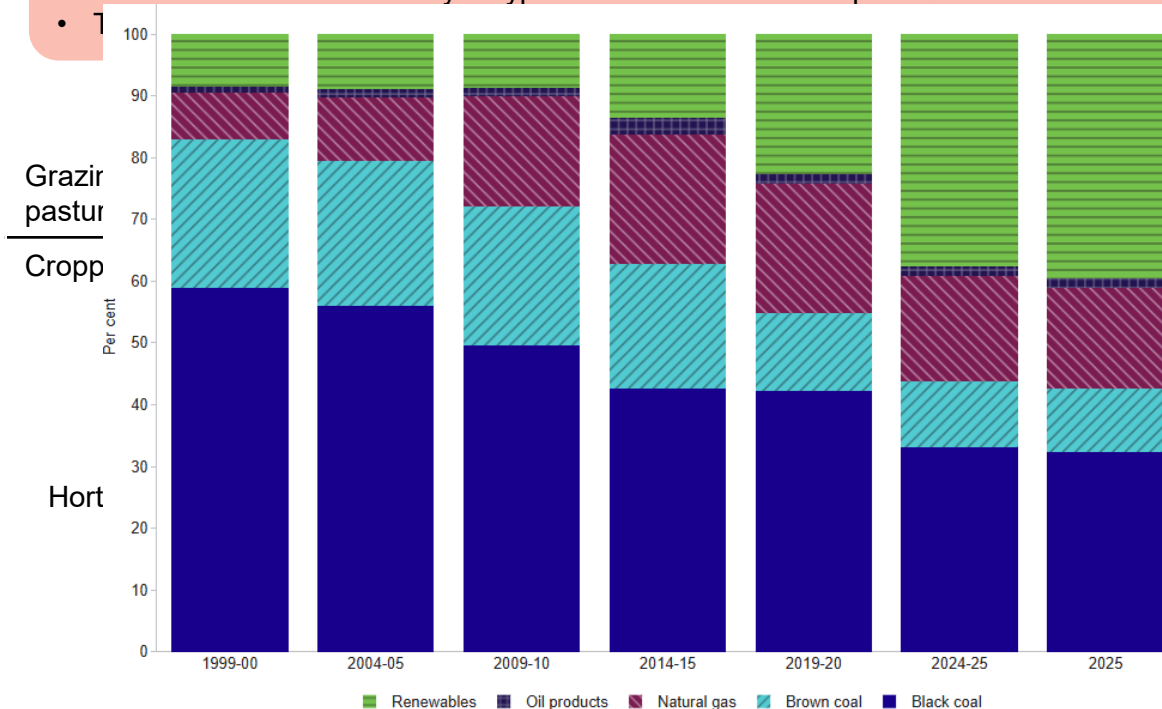


Assumed Average

Agrivoltaics potential in the Australian context

Assumptions:

- Avg. annual radiation of 1534 kWh/m²/year
- Power conversion efficiency of typical commercial c-Si PV panel of 22% and monofacial
- 1



Huge potential!
With energy storage

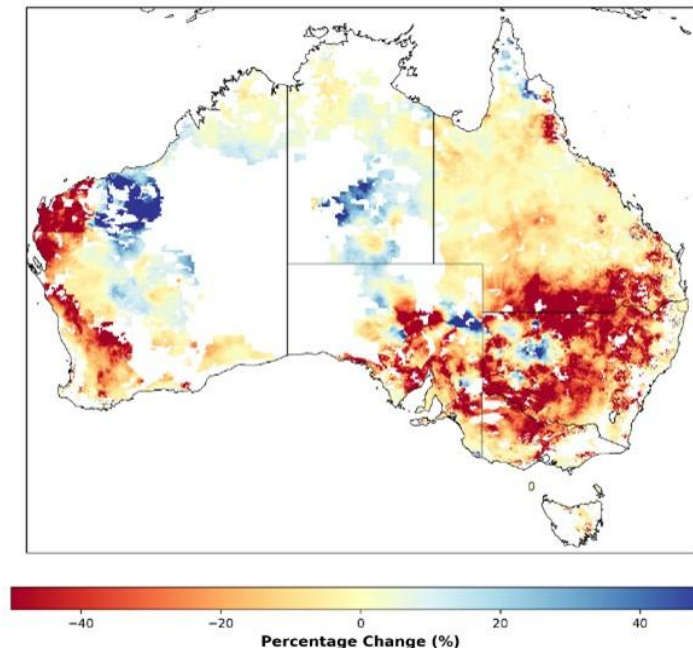
Fossil fuels sources contributed 60.5% of total electricity generation in 2025.
Renewables contributed 39.5% with solar contributing 19.6%.

Agrivoltaics potential in the Australian context

Despite around 70% of agriculture's production is exported and the value of exports has increased, climate variability has affected farm profitability over the long term.

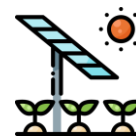
Agrivoltaics has the potential to mitigate climate change, improve soil conditions and increase water use efficiency, but **local** demonstrations and experimentation are required

Change in average annual farm profitability
2001-2023 relative to 1950-2000



Key take-aways

- ✓ **Agrivoltaics is a promising dual-use land strategy** that has demonstrated its potential worldwide. However, its performance depends strongly on climate, location, system design, scale and crop selection. **Australian conditions therefore require local validation**, while integrated models can provide an initial indication of suitable designs.
- ✓ **Spectrally selective PV technologies offer an emerging research direction**, enabling the solar spectrum to be shared more efficiently between crops and PV.
- ✓ **Australia has great agrivoltaic potential**: deploying systems on even a small proportion of its agricultural land could generate considerable amounts of renewable electricity.
- ✓ **Widespread implementation will also depend on overcoming non-technical barriers**, including farmer and public acceptance, investment costs and returns, supportive policies and regulations, and viable business models.



Acknowledgements

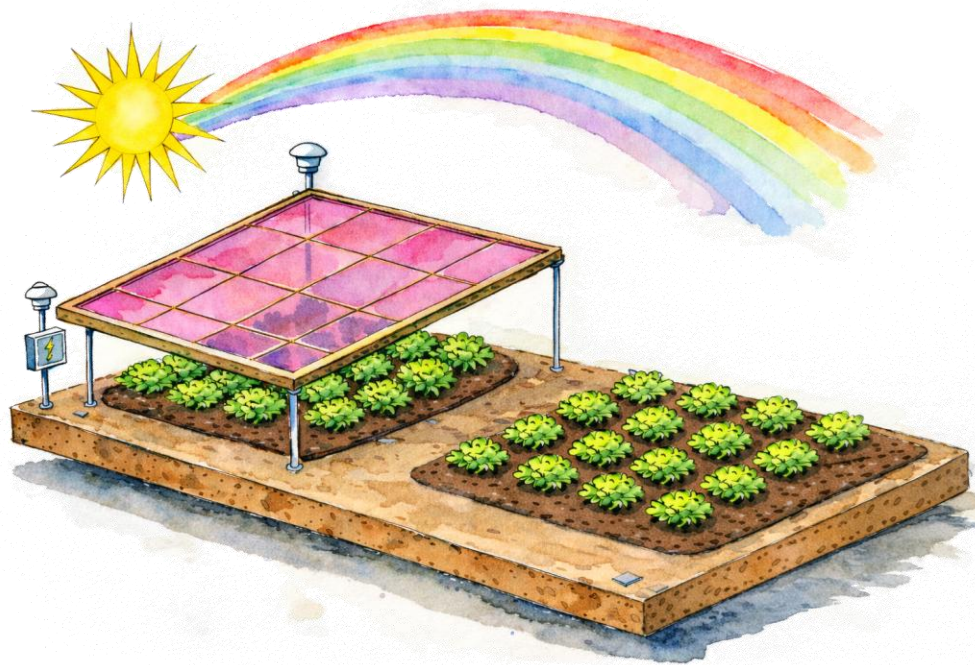


ACDC Group

Thank you for your attention!

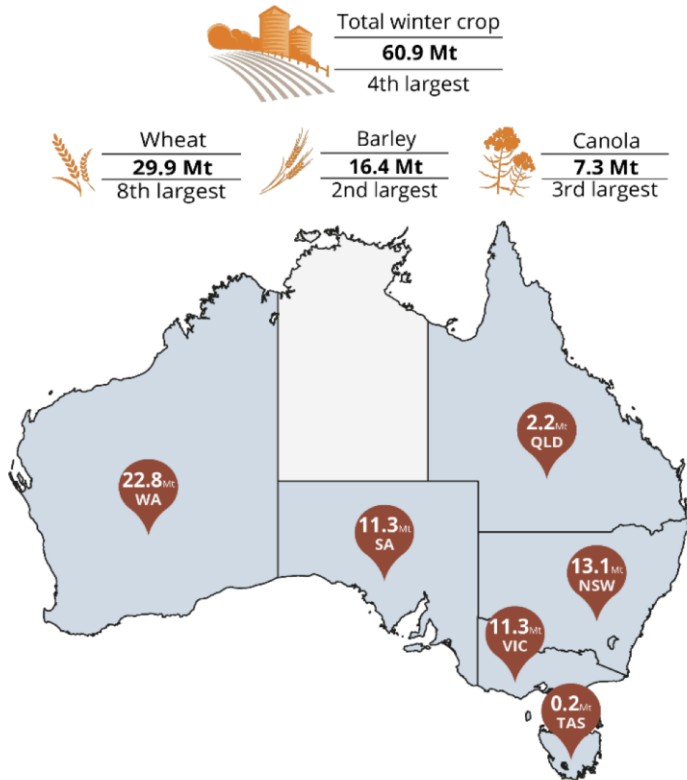


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3rd Sep 2026



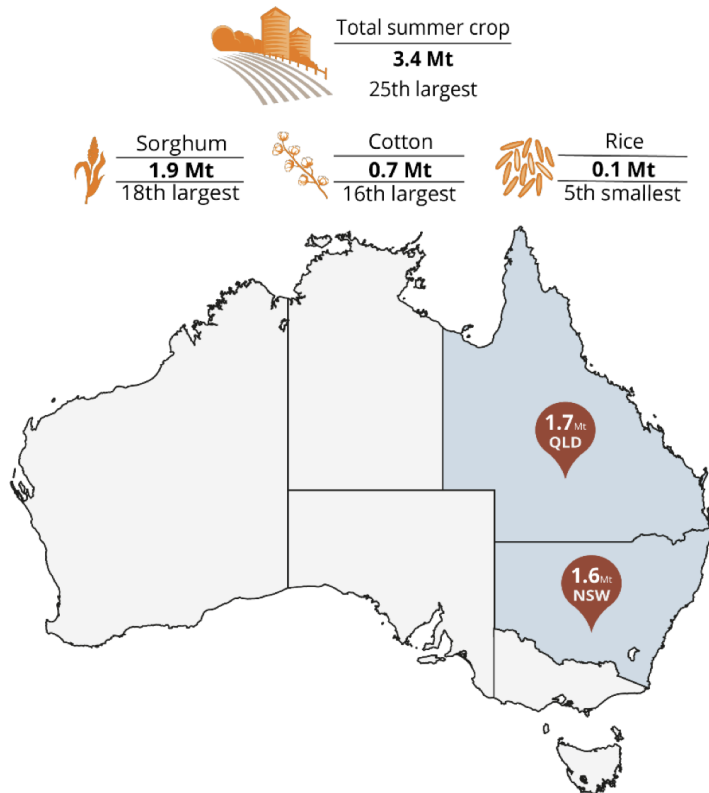
Back up slides

Figure 1 Australian winter crop production, 2026–27



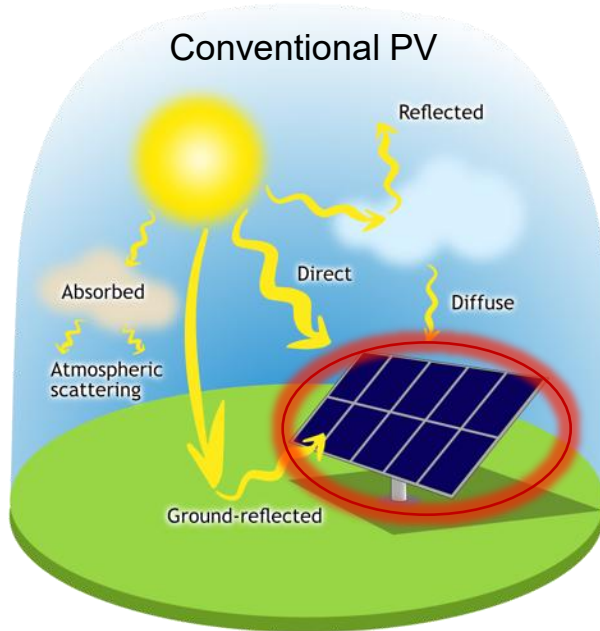
Source: ABARES

Figure 2 Australian summer crop production, 2026–27

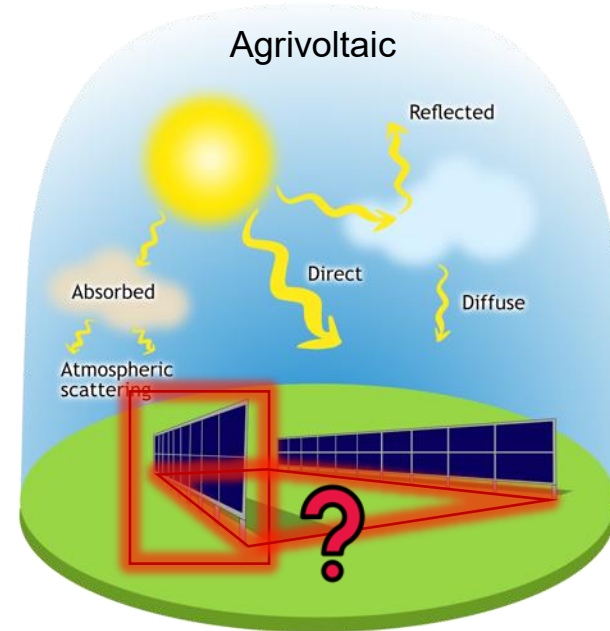


Source: ABARES

Solar Irradiance Assessment



To assess the **available solar potential** and the **amount of energy** that the **photovoltaic (PV) system** can convert from the Sun



+ To assess the **received sunlight** or the **amount of photosynthetically active radiation (PAR)** that the **crops** can use for photosynthesis and biomass production

Solar Irradiance Components in Agrivoltaics

Kärro Prästgård, Västerås, Sweden

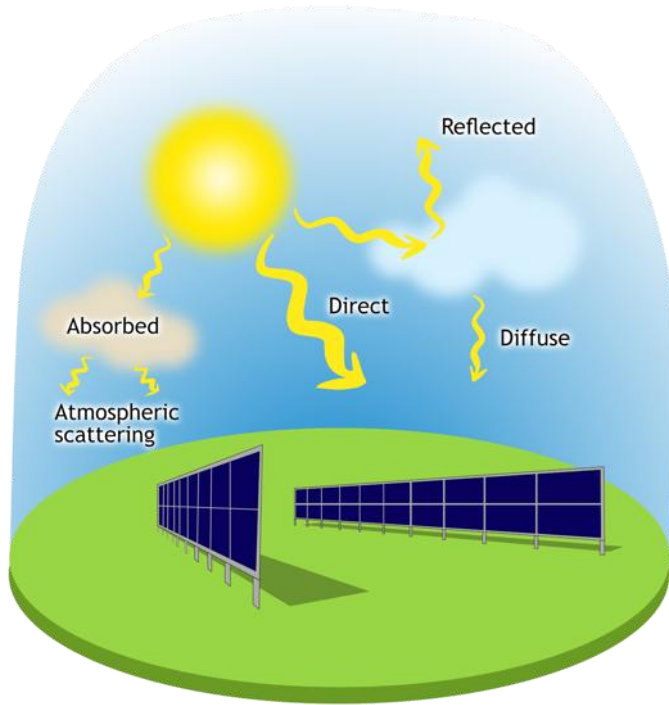
Shaded crops:
diffuse PAR + reflected PAR

Non-shaded crops:
direct PAR + diffuse PAR + reflected PAR

PAR is more efficient for canopy photosynthesis under conditions of **diffuse PAR** than direct PAR per unit of total PAR.¹



Decomposition models



Common measured parameter

Expensive sensors

$$GHI = DNI \times \cos(Z) + DHI$$

Global horizontal irradiance (GHI)
Diffuse horizontal irradiance (DHI)
Direct normal irradiance (DNI)
Solar zenith angle (Z)

Decomposition models also known as separation or partitioning models are empirical models aimed to obtain the DHI from GHI.

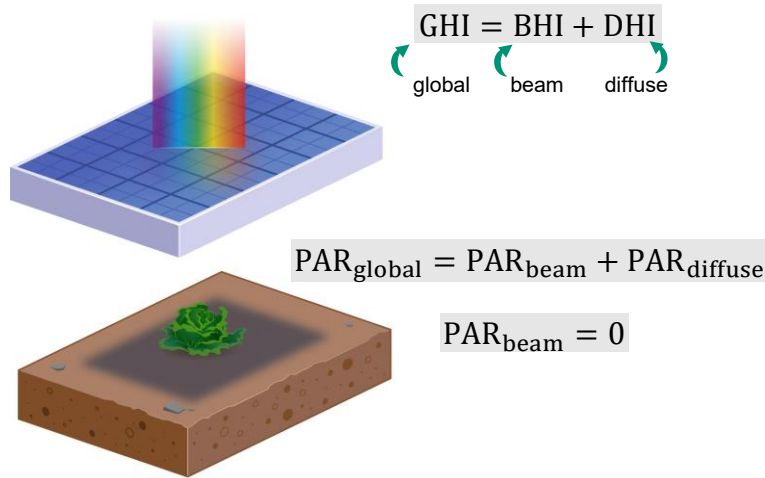
Limited PAR components measurements

For broadband irradiance (GHI): hundreds of models¹
For global PAR: limited models²

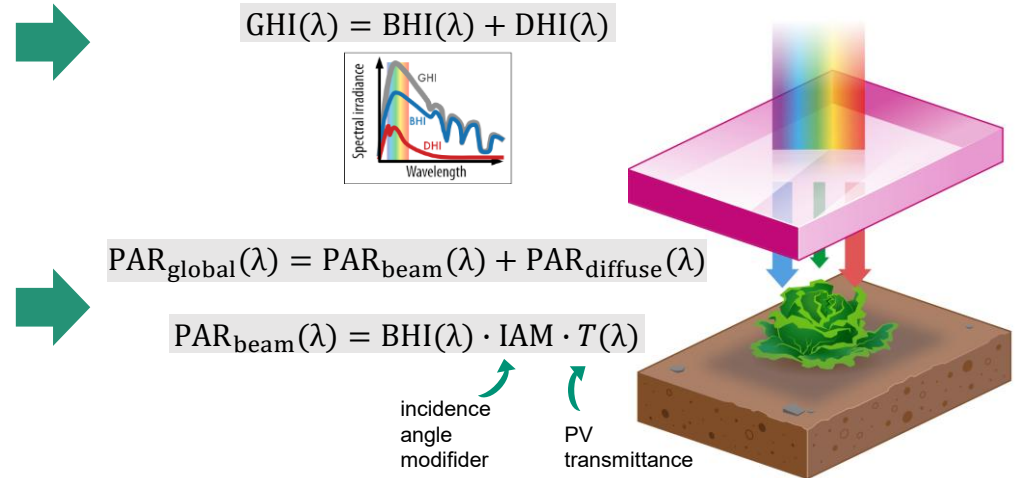
1. Gueymard & Ruiz-Arias (2016). Extensive worldwide validation and climate sensitivity analysis of direct irradiance predictions from 1-min global irradiance. Sol. Energy, 83(3), 432-444.

2. Ferrera-Cobos et al. (2020). Analysis of spatial and temporal variability of the PAR/GHI ratio and PAR modeling based on two satellite estimates. Remote Sens., 12(8), 1262.

Broadband



Spectral^{1,2}



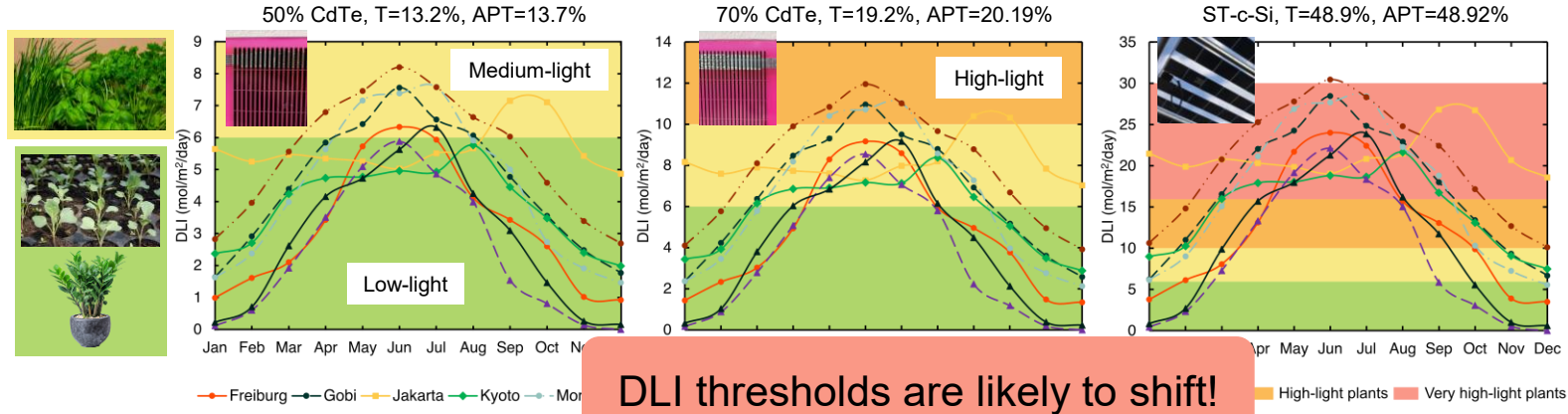
1. Fernández et al. (2022). Global Energy Assessment of the Potential of Photovoltaics for Greenhouse Farming. Appl. Energy, 309, 118474.

2. Safat Dipta et al. (2022). Estimating the Potential for Semitransparent Organic Solar Cells in Agrophotovoltaic Greenhouses. Appl. Energy, 328, 120208.

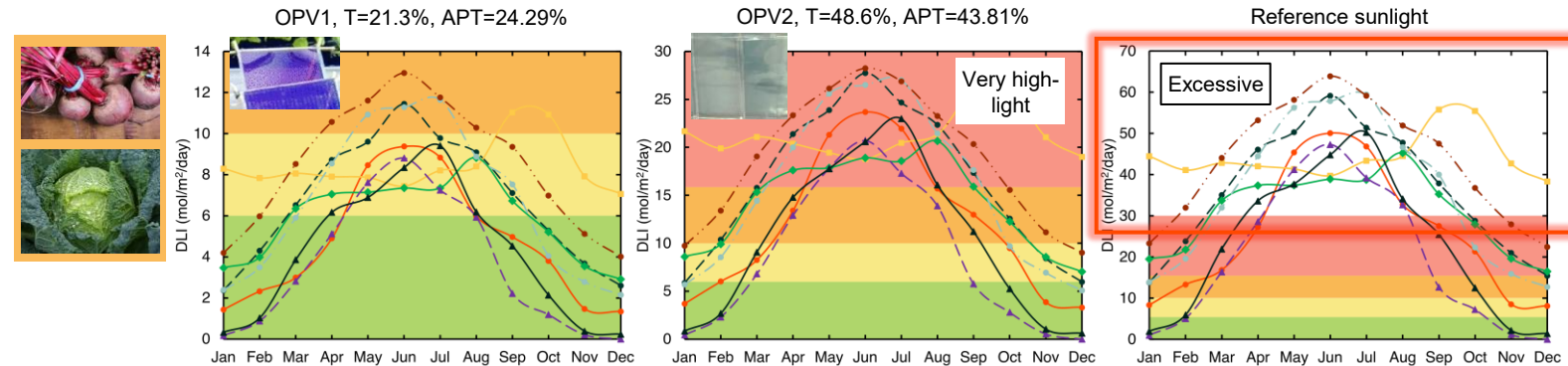
Illustration from: Ma Lu et al. (2024). Wavelength-selective solar photovoltaic systems to enhance the spectral sharing of sunlight in agrivoltaics. Joule, 8, 2483–2522.

Results Crop suitability analysis

T = average transmittance (PAR region)
APT = average photosynthetic transmittance



DLI thresholds are likely to shift!



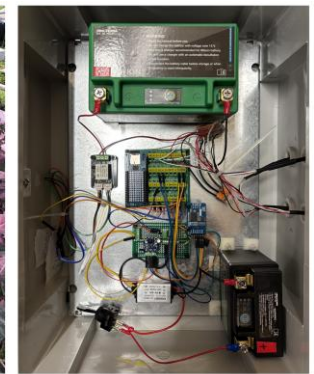
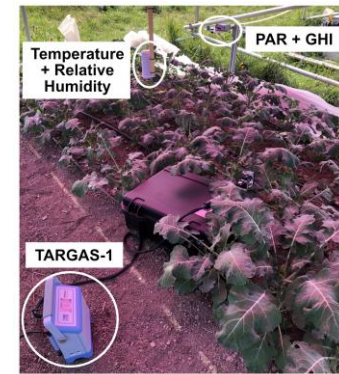
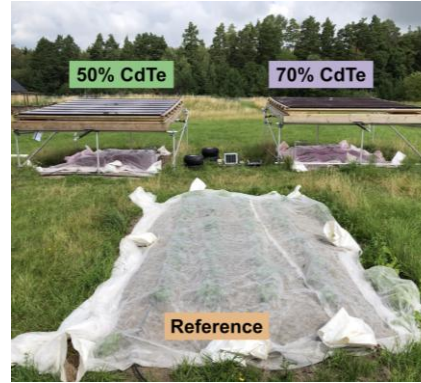
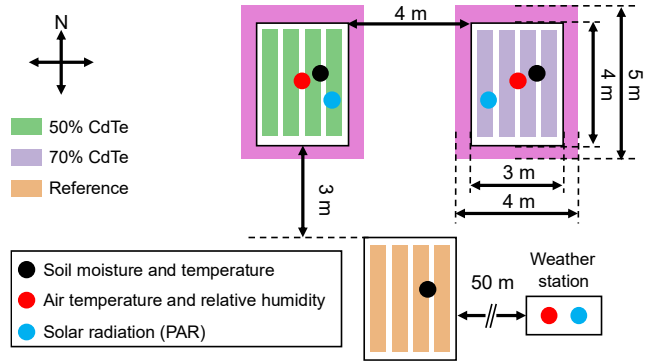
Broccoli experiments

Field experiments
July – October
2024

Microclimate
monitoring and
analysis

Crop
morphology,
physiology and
yield analyses

WSPV power
output
estimation and
land productivity



DAT = Day After Transplant

DAT=0

- July 2, 2024
- Transplanting broccoli from nursery to field
- Under 3 treatments: Reference, 50% and 70% CdTe

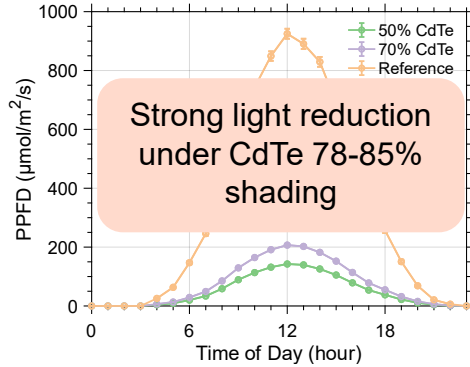
DAT=79

- September 19, 2024
- Sampling Round 1 – Maturity of broccoli in Reference
- Under 3 treatments: Reference, 50% and 70% CdTe

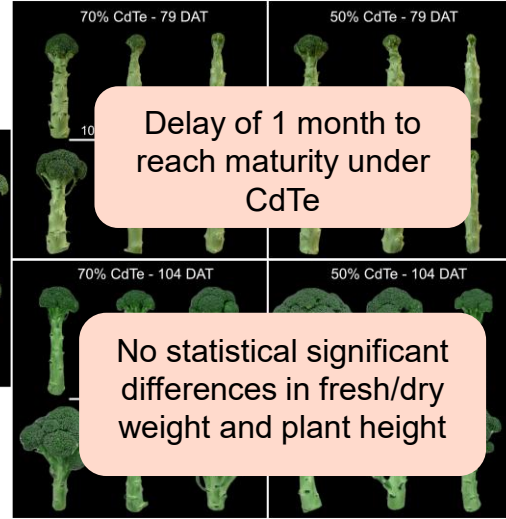
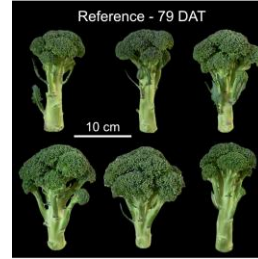
DAT=104

- October 14, 2024
- Sampling Round 2 – Maturity of broccoli under CdTe
- Under 2 treatments: 50% and 70% CdTe

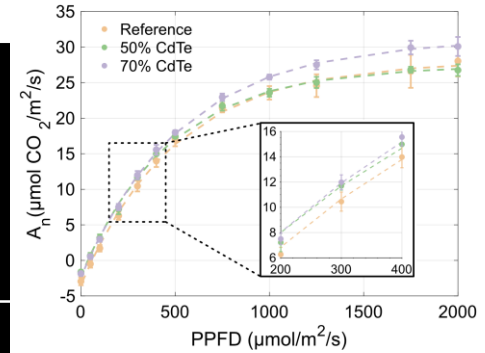
Results broccoli experiments



Average daily pattern of light intensity, bars represent $\pm$ SE around the mean value (dots)



Statistical analysis using one-way ANOVA + Tukey's HSD (n=6)



Increased Radiation Use Efficiency (RUE) up to 4.5 times

RUE = aboveground dry weight yield / total light integral

Manufacturer's datasheet
ASP-LAM2-T50, PCE = 7.2%

PCE = power conversion efficiency

Input weather data
(Jul 2– Oct 14)

System Advisor
Model™
(WSPV power
output simulation)

Land Equivalent Ratio (LER) 1 ha 50% CdTe (546 kW_p):

$$LER = \frac{Y_{crop APV}}{Y_{monocrop}} (1 - LL) + \frac{Y_{electricity APV}}{Y_{electricity PV}}$$

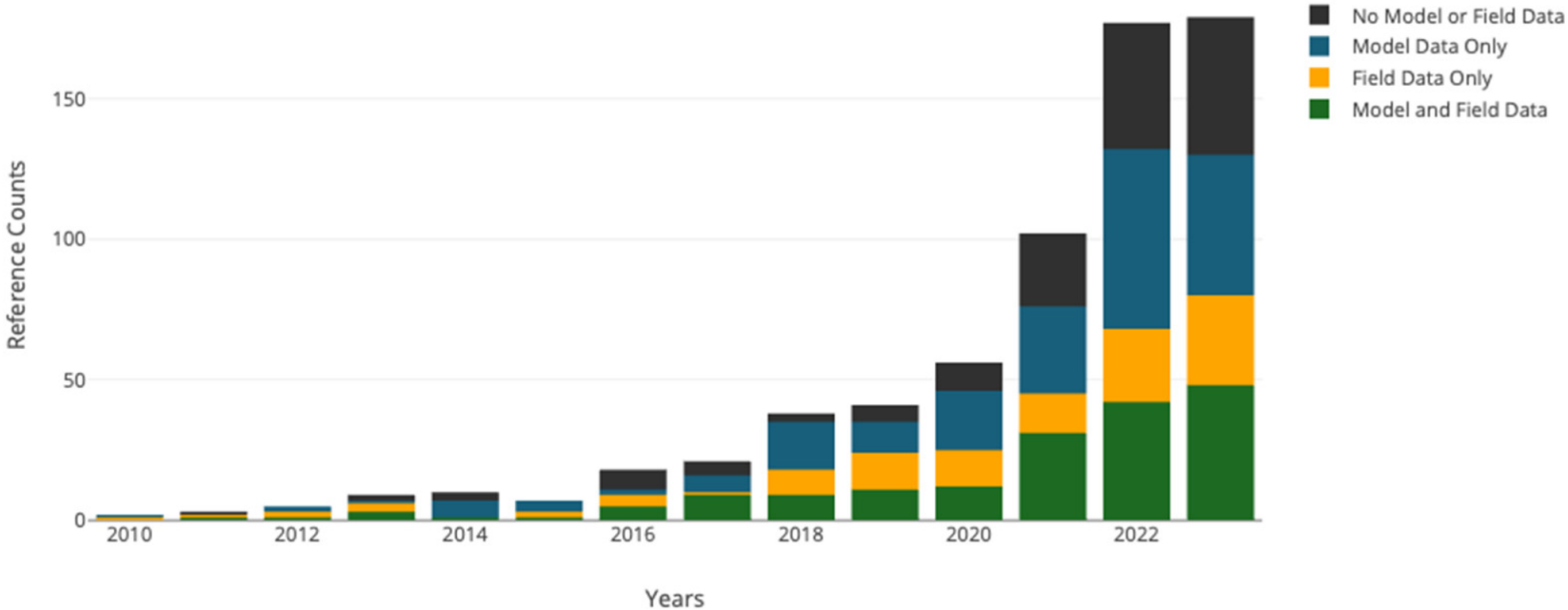
Land loss

$$LER = \frac{0.54 \text{ t DM ha}^{-1}}{0.66 \text{ t DM ha}^{-1}} (1 - 0.4) + \frac{224.7 \text{ MWh ha}^{-1}}{325.2 \text{ MWh ha}^{-1}} = 1.18$$

Conventional ground-mounted PV system¹

18% increase in land productivity

Publications Over Time



Publication Topic Counts

