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Agrivoltaic Farming Systems

Mitch Tuinstra, *Professor of Plant Breeding and Genetics, Wickersham Chair of Excellence in Agricultural Research, Scientific Director of the Institute for Plant Sciences*

Agrivoltaics Research Team

- *The Purdue AgPV research team includes:*

Rakesh Agrawal
- Chemical Engineering

Peter Bermel
- Electrical and Computer Engineering

Sylvie Brouder
- Agronomy

Margaret Gitau
- Agricultural and Biological Engineering

Juan Sesmero
- Agricultural Economics

Mitch Tunistra
- Agronomy

Agrivoltaics (AgPV) Research Platform

- *A Purdue AgPV research platform was build in 2019 with support from the National Science Foundation (NSF) under grants #1735282-NRT/10001536 and Purdue University.*

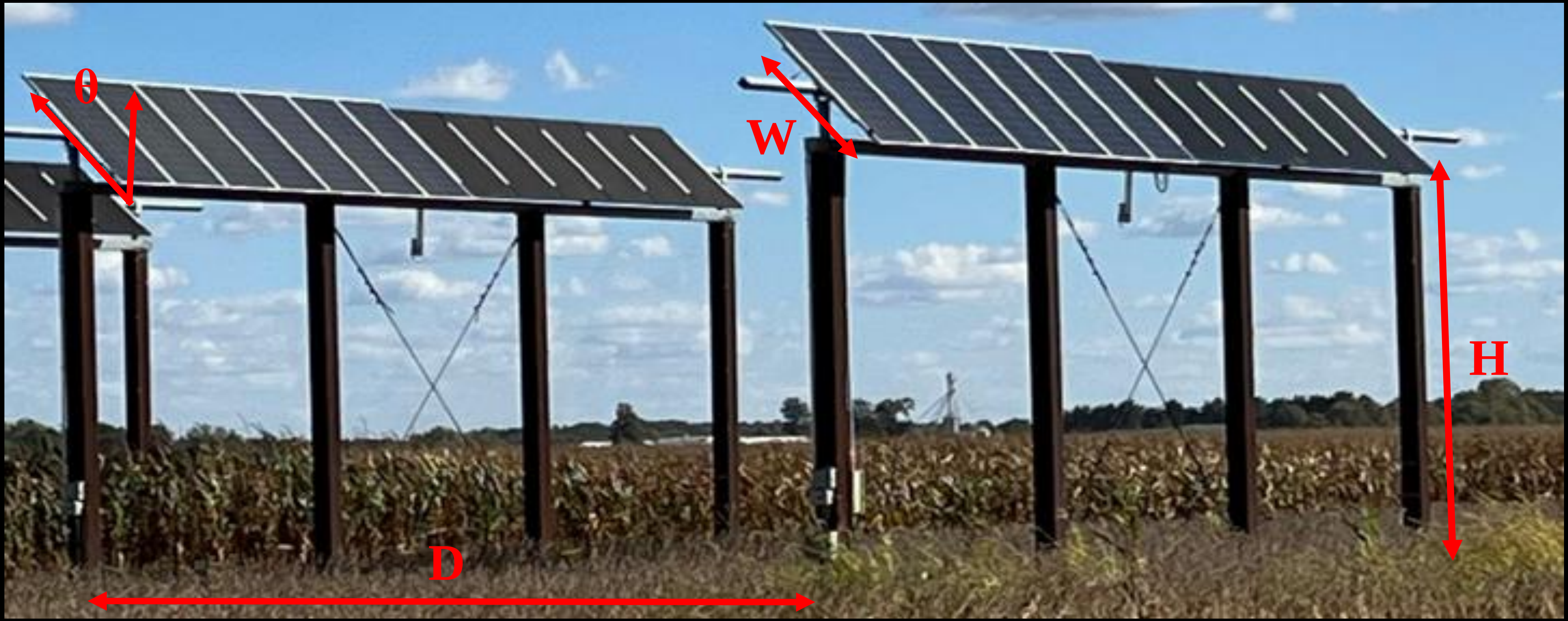
Agrivoltaics (AgPV) Research Platform

- *The impacts of AgPV systems on microclimate are being monitored using environmental sensors.*
- *Pyranometers and shadow-ring assemblies are being used to measure direct and diffused light intensities at plant height levels.*

Direct and diffused light are measured at various locations to validate shadow prediction models.

AgPV Structure and Shadow Models

- *Ray tracing and irradiance models have been developed to study the impacts of AgPV systems on shadows and light availability at the canopy level.*



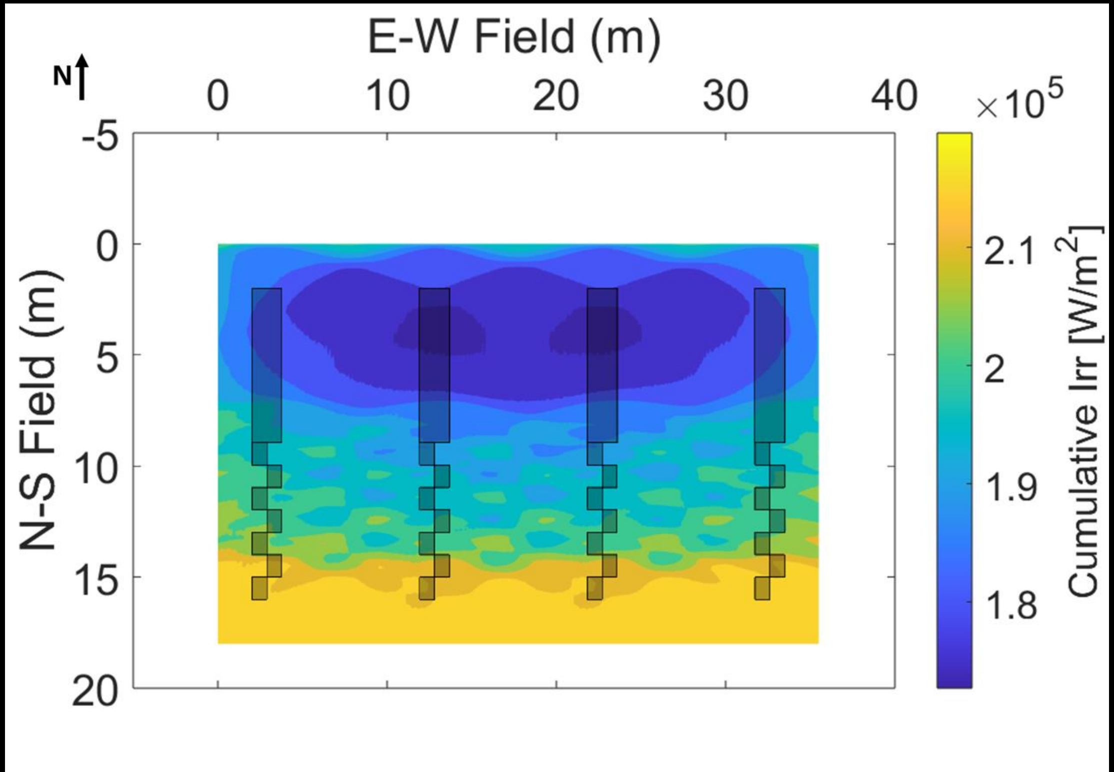
3D structure and shadow models can be used to quantify the impacts of AgPV systems on light availability.

Grubbs et al. (2024); Gupta et al. (2024)

AgPV Structure and Shadow Models

- *Measurements and simulations of cumulative irradiance distribution at ground level show that each plot is subject to a time varying irradiance profile, resulting in a separate profile for each plot.*

***AgPV Shadow Models** have been developed to predict spatial and temporal irradiance at the canopy level in any environment*



Spatial irradiance distribution at ground level.

Grubbs et al. 2024; Gupta et al. 2024; Sanchez et al. 2024

Varying Irradiance and Crop Performance

- *Corn and soybean crops have been produced under the system since 2019 with measurements of crop production, environmental attributes, and PV performance each year.*

Planting with 4-row precision planter

Harvesting with 2-row combine harvester

Varying Irradiance and Crop Performance

- *The impact of AgPV systems on crop development was determined by measuring anthesis and silking dates as well as plant and ear height.*

Anthesis dates

Silking dates

Plant and ear height

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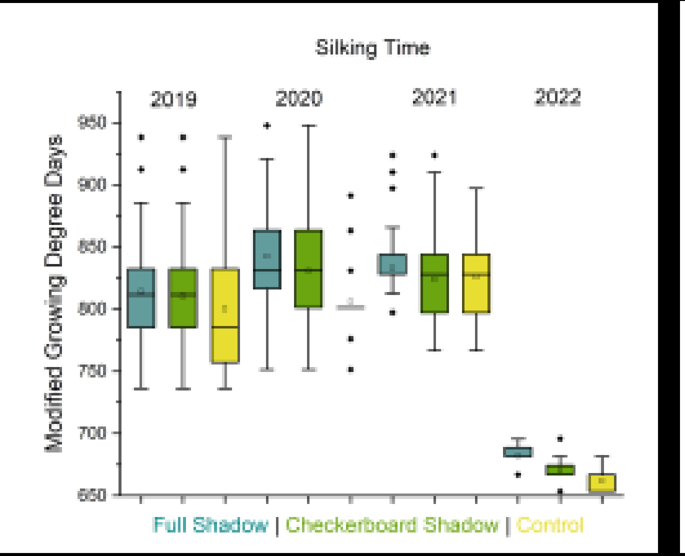
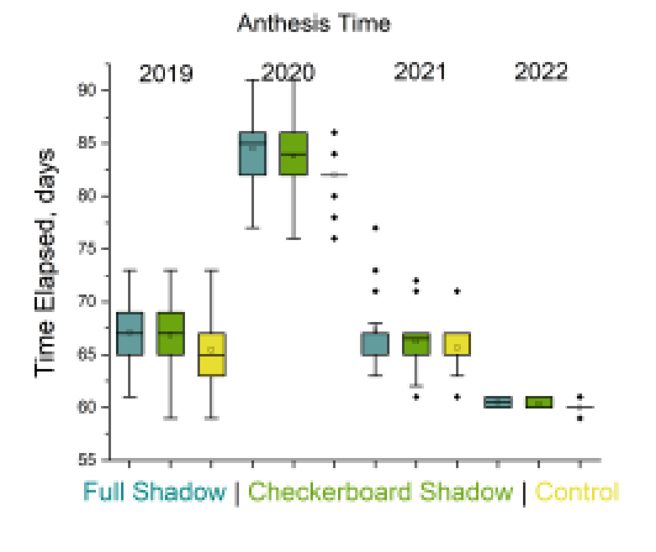
Varying Irradiance and Crop Performance

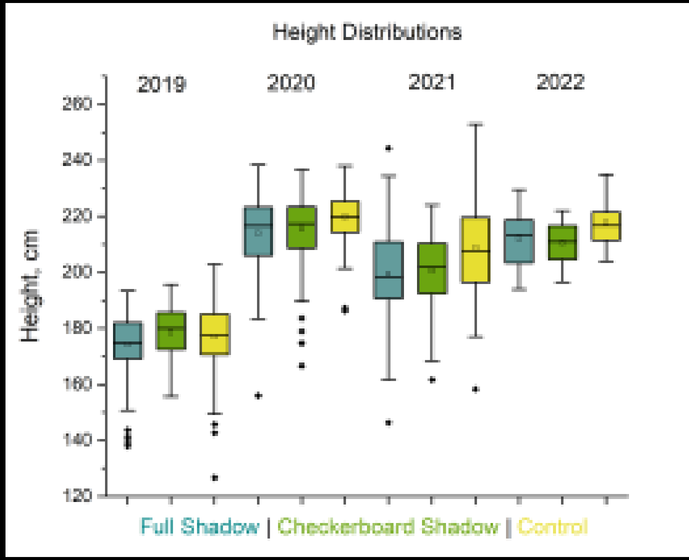
- *The impact of AgPV systems on crop development was determined by measuring anthesis and silking dates as well as plant and ear height.*



Silking dates



Anthesis dates

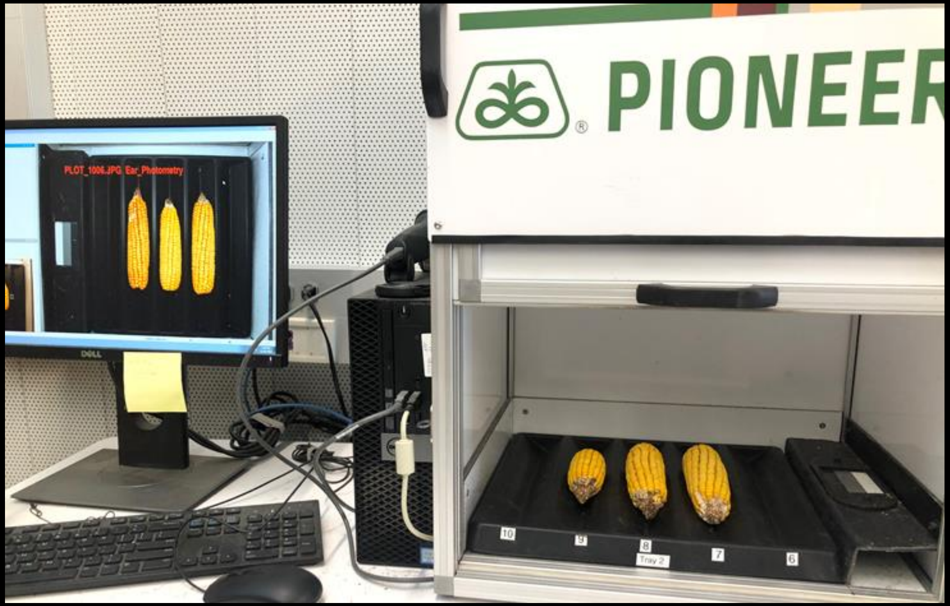


Plant height

Sanchez et al. Multi-Year Study of Maize Under Elevated Tracking Agrivoltaic System and Simplified Yield Modelling. Available at SSRN 4807752.

Varying Irradiance and Crop Performance

- *The impacts of AgPV systems on corn yields and yield components were determined by ear photometry.*



Ear Photometry System

Predictions for yield, kernels per ear, kernel fill, ear length and width, ear fill … etc.

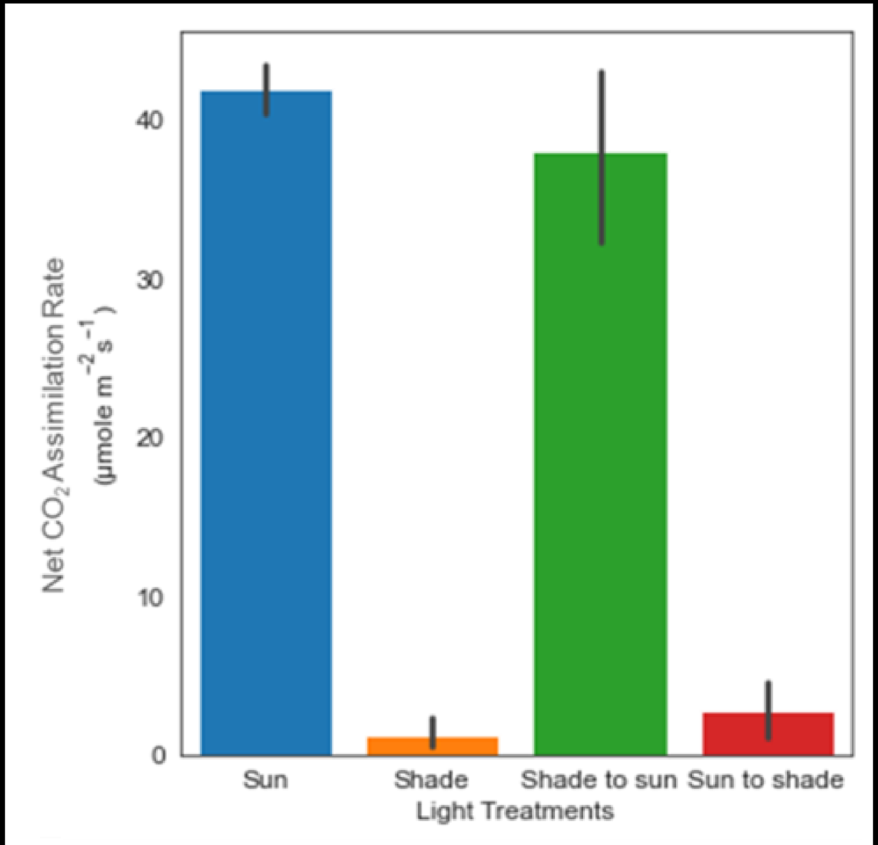
Varying Irradiance and Crop Photosynthesis

- *How are shadows contributing to changes in plant development and reductions in corn grain yield ?*

Crop photosynthetic rates were measured using a LiCOR 6800

Varying Irradiance and Crop Photosynthesis

- *Crop photosynthesis (net CO2 assimilation rates) decreased to near-zero values once a plant leaf is subject to shade from a PV module, primarily due to a decrease in stomatal conductance.*
- *Crop photosynthesis (net CO2 assimilation rates) quickly returned to normal after a period of shading.*
- *Optical simulation analyses are based on the assumption that when an area is in a near zero irradiance state, there is minimal photosynthetic activity and once the area transitions to another irradiance state, it normalizes to its full value within a minute.*

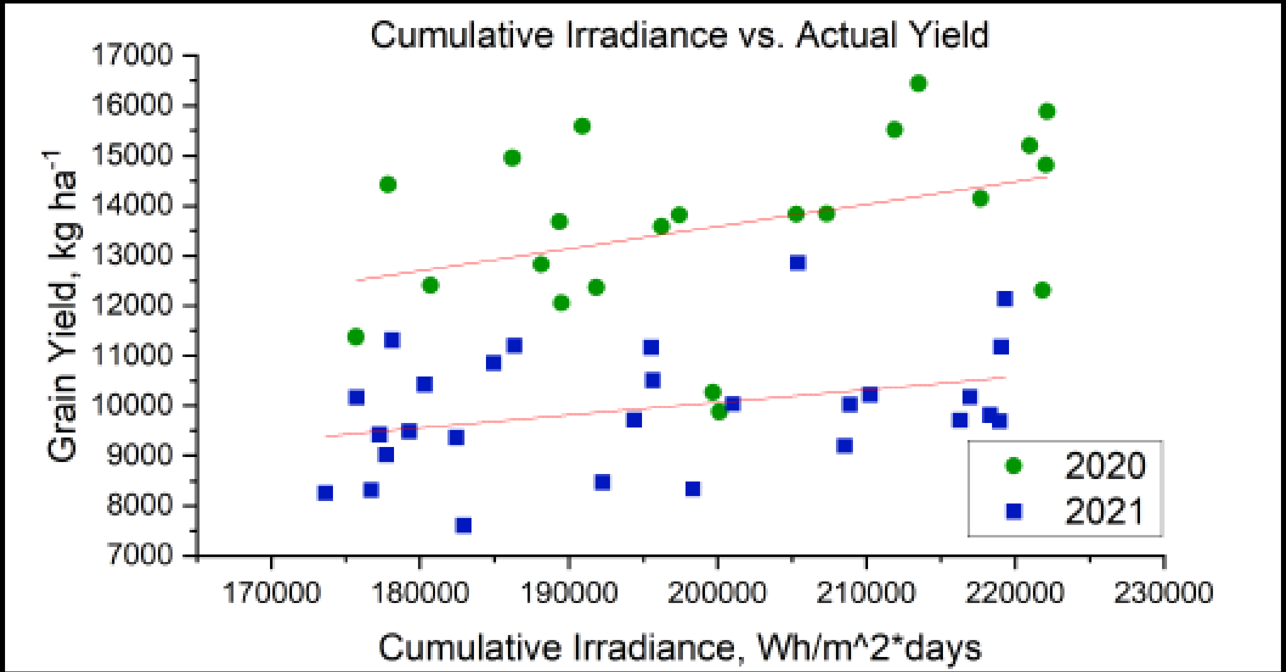


Crop photosynthetic rates are dramatically reduced under shade conditions

Grubbs et al. (2024). Renewable and Sustainable Energy Reviews, 191, p.114018.

Varying Irradiance and Crop Yield

- *Comparisons of optical energy density and observed corn grain yields show that PV shadows have a significant impact on corn crop performance.*



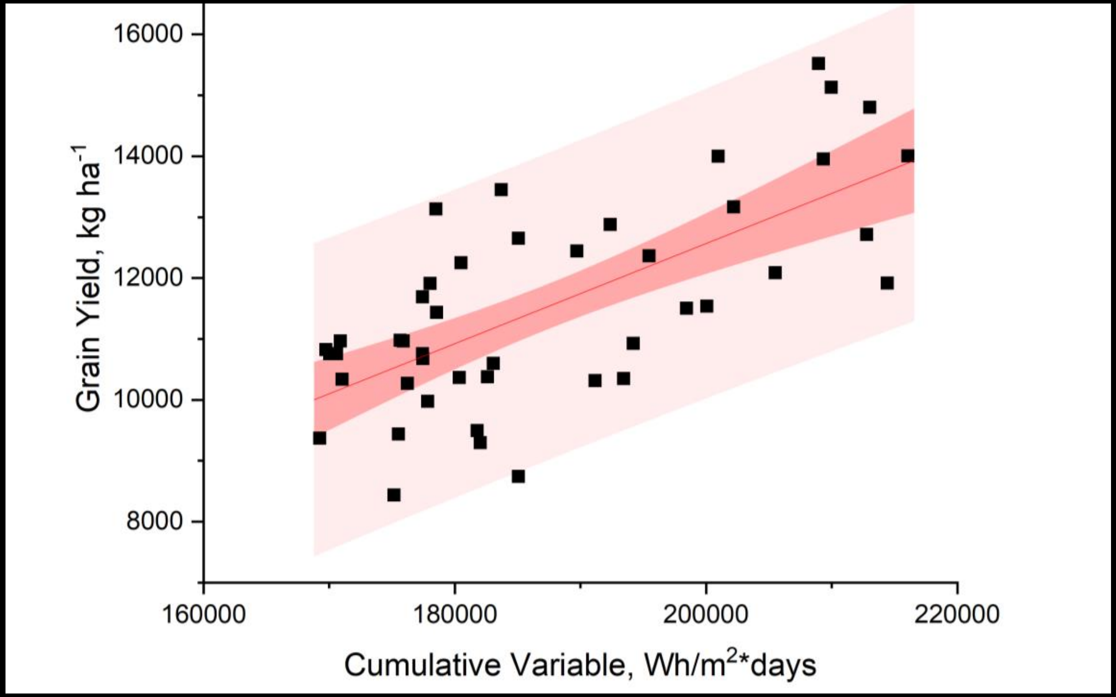
Simulated optical energy density and observed yield relationship and regression line for plant height-dependent simulations.

Sanchez et al. Multi-Year Study of Maize Under Elevated Tracking Agrivoltaic System and Simplified Yield Modelling. Available at SSRN 4807752.

Varying Irradiance and Crop Yield

- *Statistical analyses of other environmental factors indicated that soil moisture also played a key role in crop productivity.*

Statistical Models *show that cumulative irradiance and soil moisture conditions in AgPV systems drive variation in crop performance*

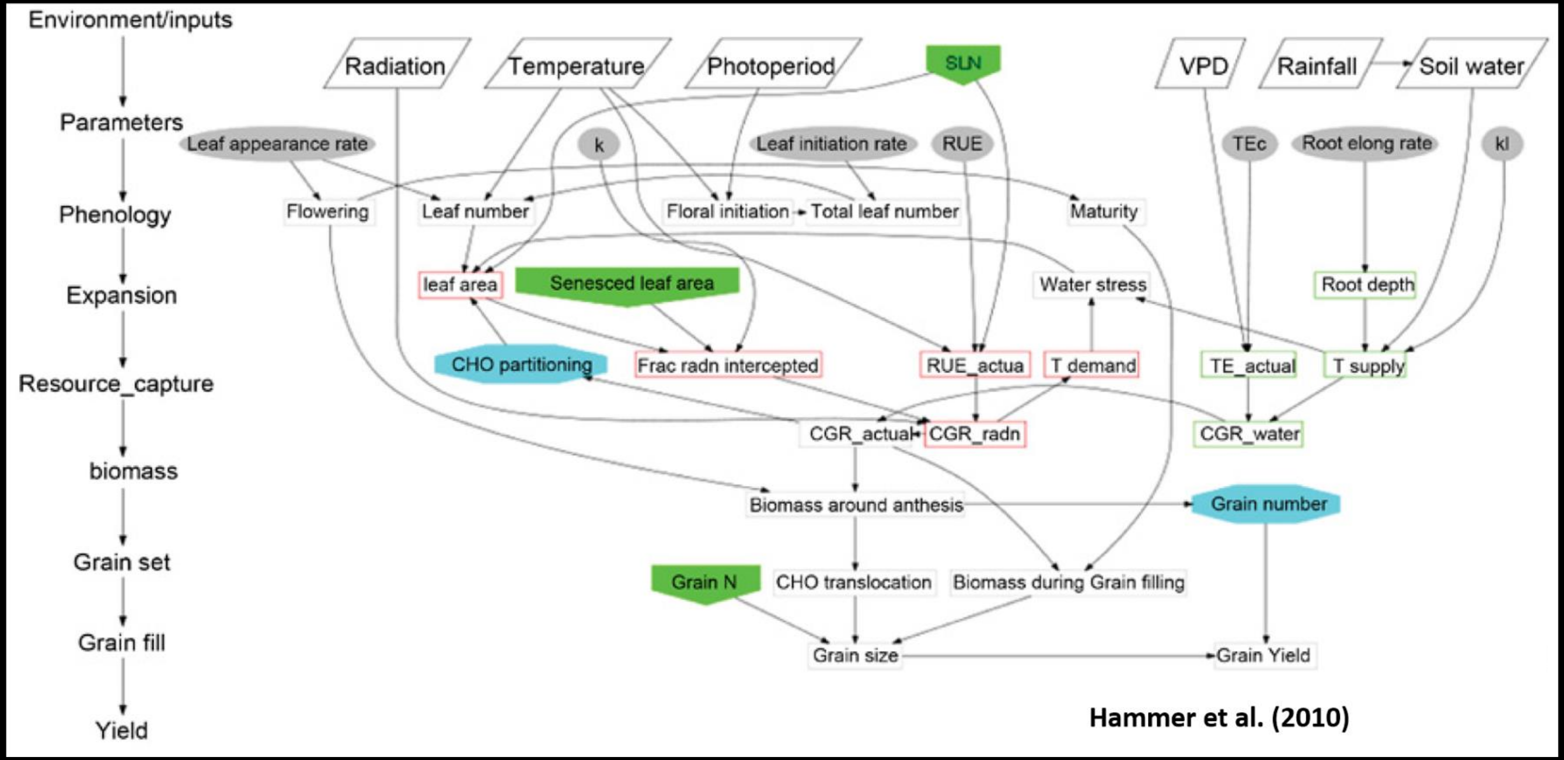


Cumulative Variable is an environmental index that integrates soil moisture and irradiance (r^2 = 0.48).

Sanchez et al. Multi-Year Study of Maize Under Elevated Tracking Agrivoltaic System and Simplified Yield Modelling. Available at SSRN 4807752.

Optimizing AgPV System Performance

- *Crop performance data are being used to parameterize the Agricultural Production Systems sIMulator (APSIM) biophysical crop model to study and optimize crop production in agrivoltaic systems..*



Agricultural Production Systems sIMulator (APSIM) biophysical crop model inputs and outputs

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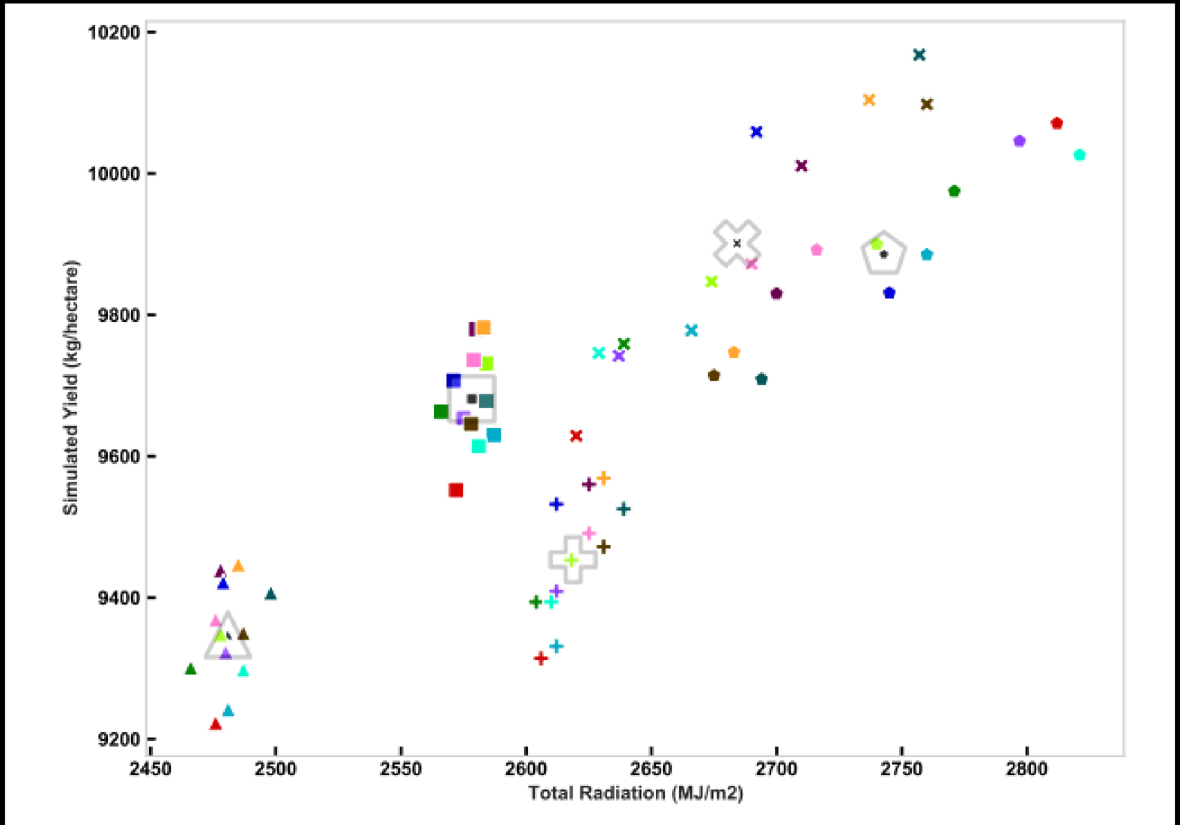
Optimizing AgPV System Performance

- *Parameterized APSIM crop models are being used to simulate crop performance for an array of AgPV structures and operational situations.*

Biophysical Crop Models *can be used to simulate crop performance for an array of AgPV structures and operational situations*



Gupta et al. (2024)

Optimizing AgPV System Performance

- *AgPV systems can be optimized for food or energy production through manipulation of solar tracking and anti-tracking.*

Performance chart with energy generation and crop yields under various AgPV layouts.

Layout or tracking scheme	Energy generation per year (MWh)	Energy generation per year (% of ST)	Average Predicted Yield loss (t/ha)
Solar Tracking	19.7	100%	0.94
Ideal Anti-Tracking during the Cropping Season	9.9	50%	0
Critical Time-Anti-Tracking (DOY - 225 to 265)	17.2	87%	0.70

Grubbs et al. (2024). Renewable and Sustainable Energy Reviews, 191, p.114018.

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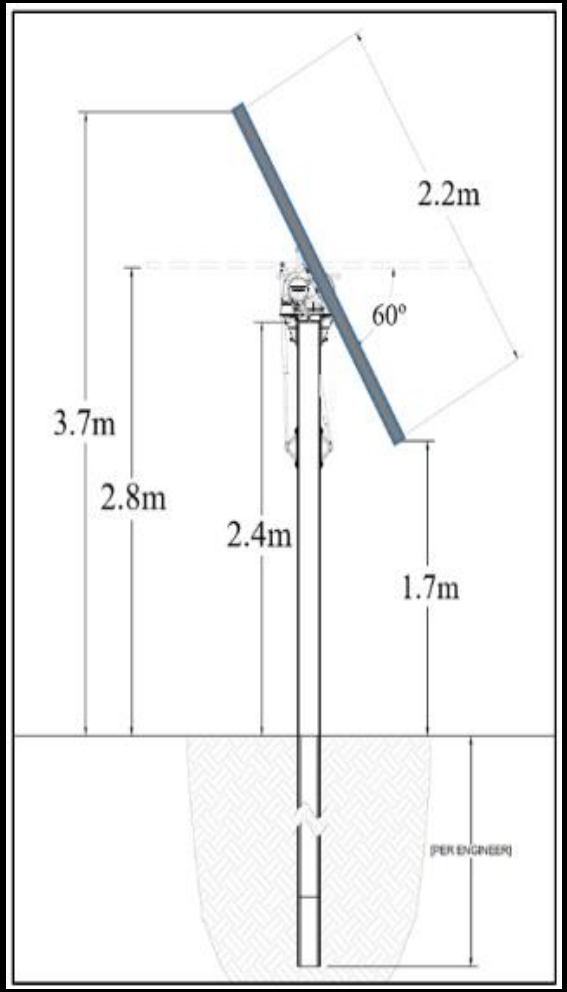
Optimizing AgPV Structure Designs

- *The use of tall AgPV structures in commercial agriculture is limited by high CAPEX costs.*

Purdue AgPV research platform

Optimizing AgPV Structure Designs

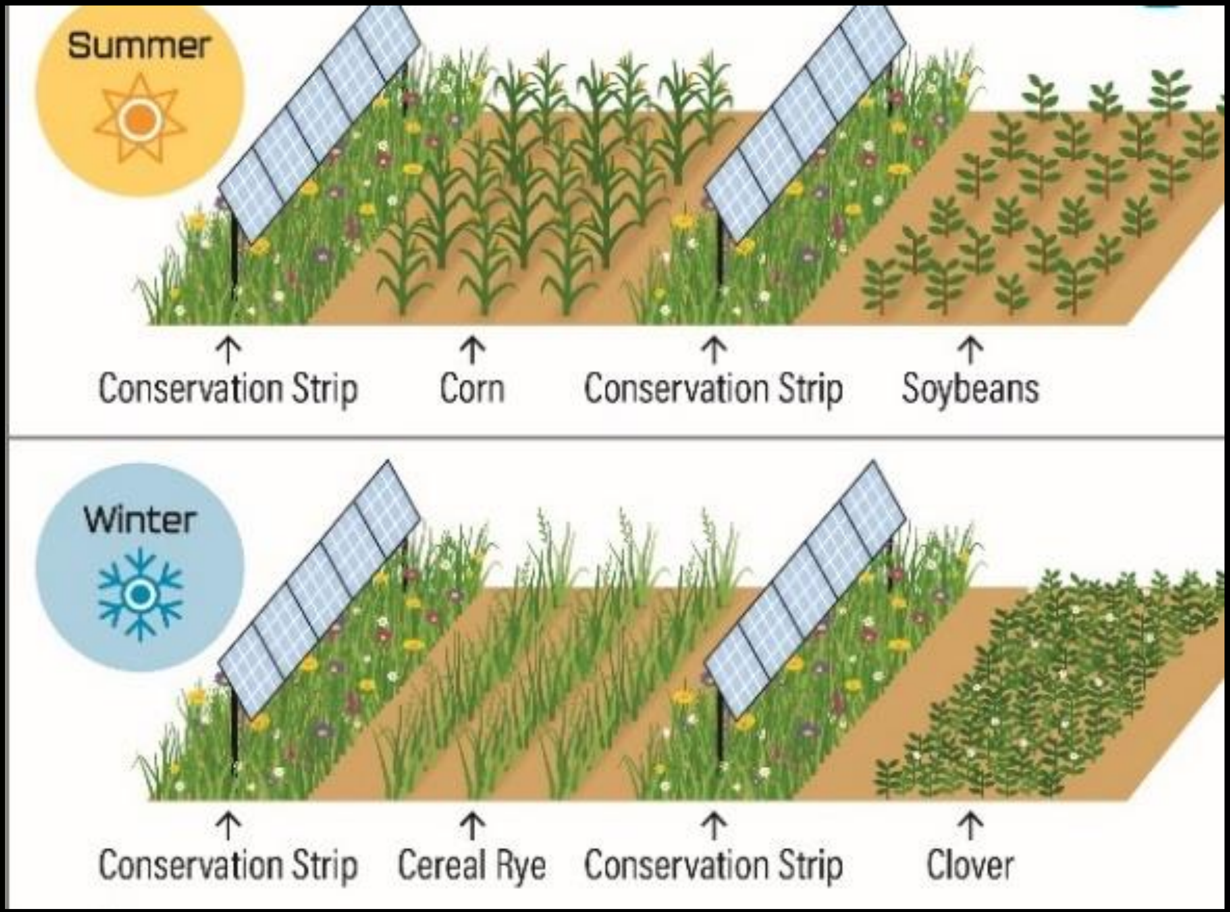
- *The use of tall AgPV structures in commercial agriculture is limited by high CAPEX costs.*
- *New AgPV prototypes are being proposed that are dictated by height of plants growing beneath and between PV arrays and not by farm machinery height.*
- *The solar trackers on the proposed AgPV systms increase the angle of the panels to 60º to increase flexibility of access for farming equipment.*



Low-CAPEX AgPV system

Creating Regenerative AgPV Systems

- *With the reduced-height AgPV design, the lower edge of the panel in tracking mode is 1.7m to enable planting of conservation strips containing diverse plant species beneath the arrays to increase biodiversity and reduce soil erosion losses.*
- *"Short-Corn" hybrids will be used to reduce or eliminate shading of low-height PV panels.*
- *Cover crops can be integrated into regenerative AgPV systems to improve soil health.*



Regenerative AgPV Systems

Conclusions

- *The average drop in grain yield of corn in the fully shaded area across four years was 7.7% while the average shading in the same location was approximately 20-25%.*
- *The integration of PV shadow models, micrometeorological condition analyses, and experimentally validated ray-tracing and irradiance modeling with empirical cropping system research and biophysical crop models can predict crop and energy production in AgPV systems.*
- *These models have identified opportunities for near-neutral coproduction of food and energy leveraging already existing hardware for a viable pathway for widespread solar implementation throughout the contiguous United States.*