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Optimizing Fixed-Tilt Agrivoltaic System Design for Lowland Rice Across Japan#

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ABSTRACT

Agrivoltaic systems (AVSs) provide a promising strategy to reconcile Japan's competing land demands for renewable energy and food production. Yet the spatial distribution of AVS designs that reflect the country's pronounced climatic diversity remains poorly quantified. This study performed a nation-wide optimization of fixed-tilt, elevated AVS designs for lowland rice cultivation by coupling 1-km MONSOLA-20 monthly radiation data with a computationally efficient crop-light model. For every one of 376,871 grid cells we identified the projected ground coverage ratio (pGCR) that balances power production and agricultural environmental impacts. The resulting optimal pGCR averaged 20.33 %, yielded an average land-equivalent ratio (LER) of 1.64, demonstrating significantly higher land productivity compared to conventional separate production systems. The resulting AVS design map offers location-specific guidance for growers, developers, and policy-makers, thereby facilitating the responsible expansion of AVSs and the formation of resilient urban-rural food-energy partnerships in Japan.

Keywords: agrivoltaics, agrophotovoltaic, spatial analysis, crop light model, lowland rice, land equivalent ratio

NOMENCLATURE

Abbreviations	
AVS	Agrivoltaic system
pGCR	projected Ground Coverage Ratio
LER	Land Equivalent Ratio
DLI	Daily Light Integral
PAR	Photosynthetically Active Radiation
GHI	Global Horizontal Irradiation
GTI	Global Tilted Irradiation
DHI	Diffuse Horizontal Irradiation
DTI	Diffuse Tilted Irradiation
CAR	Capacity-Area Ratio

1. INTRODUCTION

As the threat of climate change intensifies, cities urgently need integrated solutions that meet food and energy demands without exacerbating environmental degradation. Japan has established a target of achieving net-zero emissions by 2050. However, the nation faces significant challenges, including limited suitable land for solar power generation, declining agricultural populations due to aging demographics, and abandonment of agricultural land [1,2]. Resolving these land-use conflicts is therefore critical to building sustainable urban–rural systems.

A promising solution is the agrivoltaic systems (AVSs), which enables the simultaneous production of crops and solar electricity on the same land. Reported benefits include enhanced land-use efficiency, reduced irrigation demand, moderated micro-climates, and more stable farm income [3–5]. Since the Ministry of Agriculture, Forestry and Fisheries (MAFF) issued a notification regarding AVSs in 2013, 5351 projects have been approved; however, 1854 cases grow ornamental rather than staple crops such as rice (*Oryza sativa* L.) [6].

To formulate appropriate AVS introduction strategies, national-scale potential evaluations based on designs that balance power generation and agricultural production are essential. However, existing optimization frameworks are so computationally intensive that national-scale studies have relied on designs validated at one or a few sites, leading to sub-optimal recommendations that ignore regional climate [7–9].

Against this backdrop, we address two research questions:

1. What AVS design maximizes electricity yield while meeting the light requirements for lowland rice across Japan's diverse climatic regions?
2. By how much can AVSs improve land-use efficiency relative to spatially separated agriculture and PV?

Using 1-km MONSOLA-20 solar-radiation data and a computationally efficient crop-light model, we map

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optimal fixed-tilt AVS designs for every grid cell in Japan and quantify the corresponding gains in land productivity.

2. MATERIAL AND METHODS

This section describes the workflow developed to identify optimal designs for fixed-tilt overhead AVS suitable for lowland rice cultivation in Japan. Starting from monthly meteorological data extracted from the MONSOLA-20 solar radiation database at 1-km resolution, we ① estimated crop canopy DLI under various design parameter conditions, ② identified design parameters that maximize power output while meeting crop light requirements, and ③ computed LER as a performance indicator. Figure 1 summarizes the workflow and input/output data products.

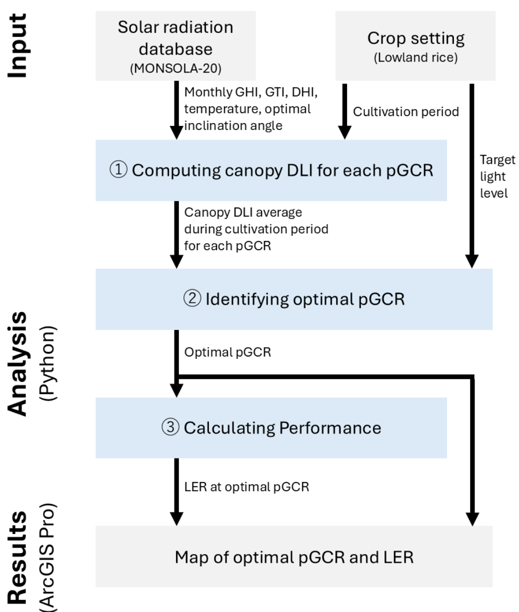

Fig. 1 Model workflow for deriving optimal design and LER

2.1 Study area and dataset

Japan spans 24°–46 ° N and 123°–146 ° E, encompassing strong latitudinal and orographic gradients. To capture this heterogeneity we employed the 1-km MONSOLA-20 archive (2010–2018), which supplies monthly means of global horizontal irradiation (GHI), global tilted irradiation (GTI), diffuse horizontal irradiation (DHI), temperature, and site-specific optimal tilt angle for each of 376,871 land grid cells [10].

2.2 Settings for the PV structure and crops

Figure 2 presents the AVS configuration examined in this study. Simulations were conducted assuming a fixed-tilt overhead AVS, currently the most prevalent type in Japan [11]. We assumed installation of monofacial monocrystalline silicon modules (2.0 m × 1.0 m, rated output 400 Wp) at a minimum clearance height of 3 m to facilitate mechanized rice cultivation. The module tilt and azimuth angles were set to the local annual optimal angles for power generation (ranging from 17° to 48°) as provided by MONSOLA-20, which account for latitude and horizon effects. The design variable pGCR was defined as the ratio of the horizontal projected area of PV modules to the underlying agricultural land area (equivalent to the ratio of a panel's projected length to row spacing). To avoid capacity factor losses due to self-shading, we established an upper limit for pGCR based on Japanese Photovoltaic Energy Association guidelines [12]. This upper limit is defined as the pGCR when row spacing is set to the shortest distance preventing inter-row shading at 09:00 and 15:00 on the winter solstice, contingent upon latitude, longitude, and module tilts.

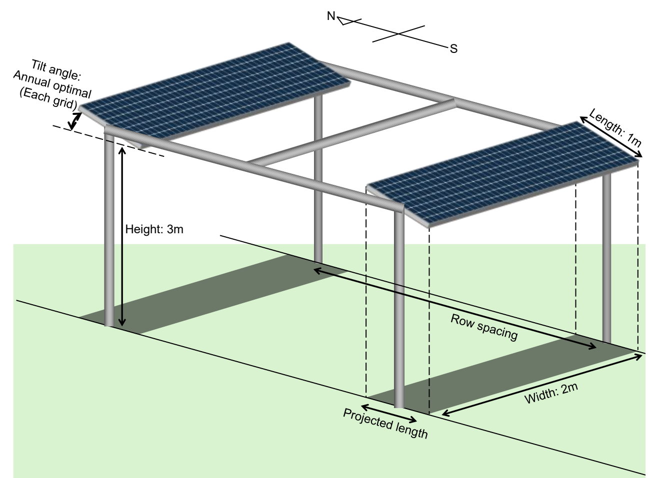

Fig. 2 Schematic of the elevated fixed-tilt AVS used in this study

We adopted the daily light integral (DLI), the integrated daily value of photosynthetic photon flux density (PPFD), as the primary indicator of the light environment for crop growth. We defined a target DLI required for sustainable crop growth; an AVS design was considered agriculturally viable if the DLI at the crop canopy met or exceeded this target. However, research on dynamic microclimate models responsive to AVS design parameters remains insufficient. Therefore, DLI was selected as the most critical microclimate parameter for this large-scale geospatial assessment.

Lowland rice, a C3 cereal, was selected as the reference crop due to its economic and cultural significance and its widespread cultivation across Japan. The cultivation period was set from May to October, corresponding to conventional transplanting and harvesting schedules [13]. Based on previous research, the target DLI for sustainable yield was set to 25 mol m^{-2} day^{-1} [14].

2.3 Canopy daily light integral estimation model

We developed a model to estimate canopy-level solar radiation intensity for identifying optimal pGCR. The model efficiently elucidated the relationship between pGCR and crop light intensity by considering diffuse attenuation and beam attenuation due to module shadows. Edge effects (additional radiation from support frame sides) and support frame shadow effects were omitted. The diffuse and direct components of solar radiation reaching the canopy surface were calculated using the following equations:

$$HCId_{diffuse} = (1 - pGCR)DTI \qquad (1)$$

$$HCId_{direct} = (GHI - DHI) - pGCR(GTI - DTI) \qquad (2)$$

Here, HCId denotes daily accumulated horizontal canopy irradiance. Diffuse attenuation was evaluated by multiplying DTI by the sky view factor, approximated by the complement of pGCR. Since MONSOLA-20 does not directly provide DTI, we approximated it using DHI in this study. Beam attenuation was evaluated by subtracting the radiation intercepted by the module surface from the total available direct horizontal radiation.

These irradiance values were then converted to canopy DLI using the following equation:

$$DLI = 3.6(HCId_{diffuse} + HCId_{direct}) \cdot PF \cdot \frac{Q}{E} \qquad (3)$$

Here, 3.6 is the conversion factor from kWh to MJ. PF is the photosynthetically active radiation (PAR) fraction for global radiation. The Q/E factor is the quanta-to-energy ratio for wavelengths of 400–700 nm (mol MJ^{-1}) [15,16].

2.4 Projected ground cover ratio optimization procedure

The optimal design was defined as that which maximizes annual electricity yield per ground area (energy-area ratio, kWh m^{-2} yr^{-1}) while minimizing adverse effects on the reference crop. Specifically, we identified the pGCR that maximized electricity yield, subject to two constraints: (1) the crop canopy DLI must remain above the minimum threshold for healthy growth (25 mol m^{-2} day^{-1}), and (2) the pGCR must not exceed the self-shading limit. For each grid cell, the model was run iteratively with pGCR values from 0% to the maximum limit in 1% increments. All computations were implemented in Python.

2.5 Land equivalent ratio calculation

LER was employed to quantify AVS double production benefits, defined by the following equation:

$$LER = \frac{Y_{crop,AV}}{Y_{crop,FL}} \cdot (1 - LL) + \frac{Y_{electricity,AV}}{Y_{electricity,GM}} \qquad (4)$$

Here, Y_{crop} and $Y_{electricity}$ represent the yields of the crop (kg m^{-2}) and electricity (kWh m^{-2} yr^{-1}), respectively, under agrivoltaic (AV), full-light (FL), and ground-mounted PV (GM) conditions. The relative crop yield ($Y_{crop,AV}/Y_{crop,FL}$) is theoretically 1.0 if the target DLI is precisely met; however, we adopted a conservative value of 0.9 to account for potential minor yield reductions. LL represents the land loss due to the footprint of the AVS support structures, for which a value of 0.1 was used in accordance with prior research [14].

The annual electricity generation, $Y_{electricity}$, was calculated using a standard method based on Japanese Industrial Standards (JIS) [17]:

$$Y_{electricity} = GTI \cdot CAR \cdot \frac{K}{G_S} \qquad (5)$$

Here, CAR denotes capacity-area ratio (kWp m^{-2}), K represents the design factor (unitless), G_S signifies standard test condition solar irradiance value (kW m^{-2}). CAR was derived from module specifications enumerated in Section 2.2 and pGCR. K is calculated based on temperature data following JIS procedures. For $Y_{electricity,GM}$ calculations, pGCR was set to the upper limit value defined in Section 2.2, and clearance height was set to 1 m. Calculations were performed in Python, and results were mapped using ArcGIS Pro (Esri: Redlands, CA, USA).

3. RESULTS

3.1 Optimal project ground cover ratio based on target light level

Figure 3 shows the distribution of optimal pGCRs for Japan when DLI of 25 mol m^{-2} day^{-1} (May to October, assuming lowland rice) was set as the target light level. Across 376,871 one-kilometer cells, the mean optimal pGCR was 20.33%, the median was 21.00%, and the standard deviation was 5.12%. In southwestern regions, the target light level could be achieved even with high pGCR values.

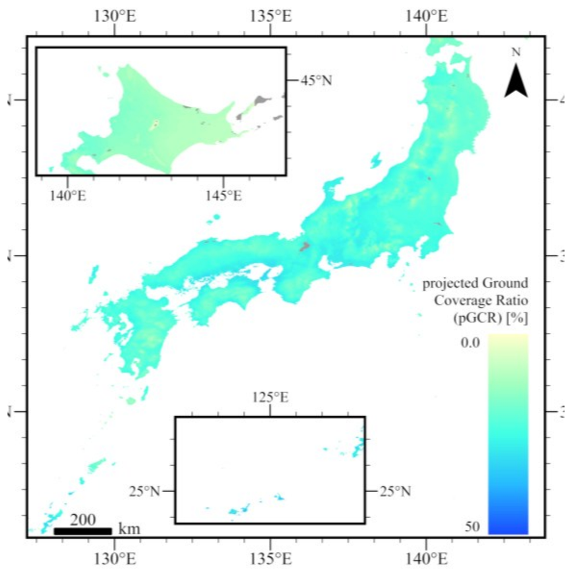

Fig. 3 Map of Optimal pGCR (Target light level: DLI of 25 mol m^{-2} day^{-1})

3.2 Land equivalent ratio under the optimal design

Figure 4 shows LER distribution under the optimal pGCR adopted in Section 3.1. The average LER was 1.64, the median was 1.66, and the standard deviation was 0.15. These results quantitatively demonstrate the high land productivity of AVS.

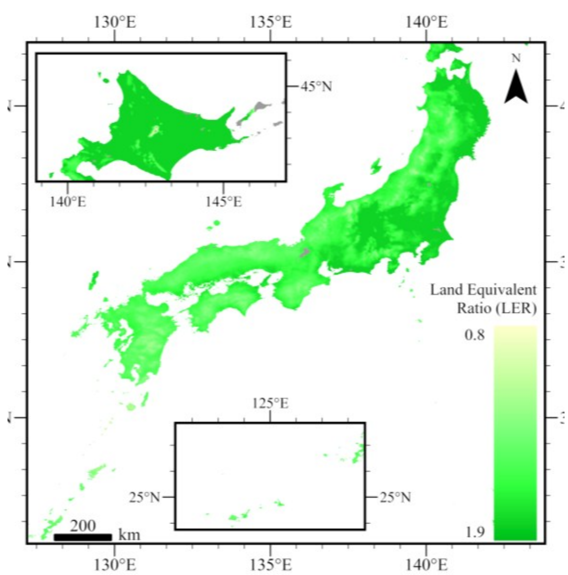

Fig. 4 LER under the optimal structure for lowland rice

4. DISCUSSION

In this study, we (1) determined the optimal pGCR that enables lowland rice to meet its light requirements while maximizing electricity yield across Japan's diverse environments using the 1-km resolution MONSOLA-20 radiation archive and our crop light intensity simulation for all 376,871 grids, and (2) quantified the extent to which AVS improves land use efficiency compared to conventional separation systems by calculating LER as a productivity indicator.

The analysis indicated a mean optimal pGCR of 20.33% ($\sigma = 5.12\%$). This value reveals significant regional variations driven by local meteorological and topographical conditions. Furthermore, divergence from existing Japanese AVS system trends was revealed [11], which may reflect that Japanese AVS projects tend to focus on fruit trees and ornamental crops that are more shade-tolerant than lowland rice.

We adopted 25 mol m^{-2} day^{-1} as the agricultural environment threshold to ensure sustainable rice yields. While precise threshold values may vary depending on crop variety and cultivation methods, the proposed workflow enables back-calculation of canopy layer DLI at AVS sites without additional PAR sensors. Consequently, the model can be empirically calibrated and validated by collecting design parameters and yield data from existing AVS sites growing various crop varieties.

The nationwide pGCR and LER maps provided by this study offer stakeholders evidence-based benchmarks for efficient and sustainable co-production of food and energy. Expanding AVS implementation with sustainable design can enhance rural energy self-sufficiency and allow surplus clean electricity to be supplied to urban centers, advancing low-carbon and resilient city realization. Furthermore, due to its high computational efficiency, our model is well-suited for integration into more comprehensive, high-resolution AVS potential assessments. Using our model to define region- and crop-specific capacity densities would enable more accurate and granular national potential assessments than have been previously researched.

5. CONCLUSIONS

AVS has the potential to revitalize rural economies while supporting urban clean energy and food demand through integrated solar power generation and agricultural production. This study presented a high-resolution (1-km), nationwide simulation to optimize fixed-tilt AVS design for lowland rice in Japan, utilizing a computationally efficient light model. The analysis estimated a mean optimal pGCR of 20.33% across 376,871 grid cells. Additionally, systems designed with these optimal pGCR values are projected to achieve a mean LER of 1.64, quantifying the substantial land-use efficiency gains of AVS compared to separated land use for agriculture and energy production.

This study's results provide AVS stakeholders with objective indicators for sustainable AVS design. Appropriately designed AVS can enhance both agricultural and energy productivity in rural areas, fostering urban-rural partnerships and contributing to the formation of resilient, low-carbon cities. As a next step, integrating these optimal design maps into national potential assessments that also consider land cover data and regulatory constraints would enable a more precise and actionable analysis.

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