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Estimation Model of Agrivoltaic Systems Maximizing for Both Photovoltaic Electricity Generation and Agricultural Production

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Abstract: Climate change and increasing food demand are global issues that require immediate attention. The agrivoltaic system, which involves installing solar panels above farmland, can simultaneously solve climate and food issues. However, current systems tend to reduce agricultural production and delay the harvest period due to shading by the solar panels. A delayed harvest period impacts the income of farmers who wish to sell produce at specific times. Incorporating a model that calculates the amount of electricity generated by solar irradiation, this study establishes a model to estimate the correct start date of cultivation for solar panel covered crops to ensure the correct harvest date and determines the expected income of farmers by calculating agricultural production and power generation. Using taro cultivation in Miyazaki Prefecture as a case study, the model estimated that the start date of cultivation should be brought forward by 23 days to ensure the ideal harvest period and agricultural production. This would prevent an opportunity loss of USD 16,000 per year for a farm area of 10,000 m^2. Furthermore, an additional income of USD 142,000 per year can be expected by adjusting shading rates for the cultivation and non-cultivation periods.

Keywords: agrivoltaic system; farming photovoltaics; solar radiation; climate change; increasing food production; photosynthetic photon flux density

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1. Introduction

1.1. Background

Climate change and increasing food demand due to population growth are global issues that need immediate attention. The agrivoltaic system can solve climate and food issues by installing solar panels at a height of 3 to 4 m above farmland to simultaneously produce agricultural products and renewable electricity. The agrivoltaic system was advocated by Dupraz et al. [1]. Schindele et al. [2] examined the effectiveness of the system for avoiding competition for land by agriculture and power generation in multiple countries.

The agrivoltaic system is promoted as a national policy in Japan [3]. Pascaris [4] pointed out that the popularization of the agrivoltaic system in the United States needs policy measures. This means that government support is needed to promote the agrivoltaic system.

The introduction of solar panels on farmland has a significant effect on agricultural growth. Dupraz et al. [1] modeled light transmission at the crop level below an array of solar panels and used a crop model to predict the productivity of the partially shaded crops. Marrou et al. [5] demonstrated the relationship between power generation and agricultural growth. Cho et al. [6] demonstrated the relationship between power generation for three different photovoltaic modules and grape growing. Chopard et al. [7] developed algorithms to support farmers to make decisions by estimating the amount of water supply according to the environmental conditions under the solar panels. These studies have led to subsequent demonstrations and research in various regions.

In Japan, the effect of shading from solar panels on agricultural growth has been observed for a wide range of agricultural products, including grains, such as rice [8], soybeans [9], and buckwheat [10]; vegetables [11], such as spinach, Japanese mustard spinach, potatoes, and asparagus; and fruits, such as strawberries and blueberries [12]. A unique study used three-dimensional geographic data to analyze areas where systems can be installed in the Kyoto Prefecture in Japan, which has many steep mountains and paddy fields for rice cultivation, which occupy 85% of the agricultural land [13]. Marrou et al. [5] found that the yields of lettuce, cucumber, and wheat decreased following the introduction of the agrivoltaic system. However, this is to be expected, as the general concept of the agrivoltaic system is that the decrease in farmers' income caused by the decrease in agricultural production due to the installation of solar panels is compensated by the income gained from selling electricity [14]. Many farmers are at risk of abandoning farming due to lower agricultural income [15]. In addition, farmers are exposed to risks such as bad weather and declining sales prices of agricultural products. Therefore, the additional income from selling electricity can mitigate the risk of declining farmers' income [16]. Nordberg et al. [17] pointed out that if CO_2 emission reductions or biodiversity improvements are achieved as a result of the system's introduction, economic benefits can also be gained through environmental credits, which have been introduced in several countries.

There have been studies on soil moisture and water flow following the introduction of the agrivoltaic system. Marrou et al. [18] studied the influence of the shading of solar panels on water flows in a soil–crop system. Zainol et al. [19] proposed that adequate water supply to the crops maintains soil moisture and ensures a stable environment under solar panels. Elamri et al. [20] proposed crop modeling for irrigated lettuces based on water management under solar panels. Hassanpour et al. [21] studied the influence of the agrivoltaic system on soil moisture, micrometeorology, and efficient water use. Parkinson and Hunt [22] examined the economic potential of the agrivoltaic system using a rainwater harvesting system in groundwater-stressed regions.

Other studies include raising pasture-raised rabbits [23] and lambs [24] as part of the agrivoltaic system.

Weselek et al. [25] and Malu et al. [26] pointed out that the agrivoltaic system is effective as a decentralized and off-grid power source in rural areas. For off-grid use, the use of solar thermal energy could be considered. The effectiveness of solar dish Stirling systems, which can also generate electricity from solar heat and heat from agricultural residuals, as a decentralized energy system have been studied [27]. A study established a detailed numerical modeling for the production of heat, electricity, and hydrogen via an electrocatalytic hydrogen production cell powered by a solar photovoltaic thermal collector as a decentralized energy system [28]. There was also a unique proposal to achieve agricultural land conservation and residential land development by introducing the system for residential land and town development [29].

The impact of the agrivoltaic system on communities has been the subject of study in many countries, such as in Japan [30], the United States [31], Palestine [32], Spain [33], Germany [34], Turkey [35], European countries [36], the Russian Federation [37], India [38], Thailand [39], and East Africa [40]. Another study addressed the impact of the system's introduction on the landscape of the target area [41].

Past studies on the agrivoltaic system generally covered the impacts on local areas; however, Adeh et al. [42] studied the impacts on the energy supply on a global scale and found that the introduction of agrivoltaic systems on less than 1% of the world's agricultural land could provide enough energy to meet the global energy demand.

The solar tracking system is effective in increasing power generation and agricultural production. Valle et al. [43] examined a solar tracking system for lettuce production. Perna et al. [44] suggested the effectiveness of installing mini-module-type solar panels together with tracking systems. From other technical perspectives, spectrally selective solar cells [45], bilayer luminescent solar concentrators [46], and special film attachments [47] have been proposed. Other studies described the effects of heat generated by solar panels. For example, the increased humidity may increase the occurrence of pests [48], while plant heat stress may occur between the photovoltaic system's bottom surface and plant height [49].

The abovementioned studies have aroused interest in the agrivoltaic system among farmers and investors. However, motivated farmers and investors still require effective models to provide information to inform their decision making regarding the system introduction.

1.2. Purpose

Current agrivoltaic systems tend to reduce agricultural production and delay the harvest season due to shading by solar panels. The delayed harvest season affects the income of farmers who wish to sell their produce at the time when the product is most highly traded in the market. In addition, the reduction in agricultural production can have a negative impact on meeting the increasing food demand. The aim of this study is to establish a model that uses solar irradiation data to determine the correct cultivation start date to ensure the ideal harvest period for specific crops under solar panels, calculate agricultural production and renewable power generation, and calculate the expected income of farmers.

We developed a model that calculated the photosynthetic photon flux density (PPFD) under solar panels by solar irradiation [50]. This study establishes a model using PPFD calculated by solar irradiation to determine the correct cultivation start date to ensure an ideal harvest period for specific crops under solar panels in order to maintain agricultural production without delaying the harvest period combined with an existing model that calculates the amount of electricity generated by solar panels based on solar irradiation.

Power generation can be maximized by installing solar panels over the entire farmland area during non-cultivation periods. However, there are concerns over how cost-effective this would be, including the labor involved in installing and removing solar panels. This study envisions the installing of the most basic fixed solar panels; however, the effects of varying shading rates between the cultivation period and non-cultivation period are examined. The results of this study can be used to study the effects of introducing technologically superior solutions in the future.

1.3. Contents and Boundaries

This study estimates the photovoltaic electricity generation and agricultural production using solar irradiation data. The amount of photovoltaic electricity generation was estimated using a model developed by Tawa et al. [51] that considers atmospheric parameters from the amount of solar irradiation published in the METPV-11 solar irradiance database. This database provides the amount of daily and hourly solar irradiation from 1990 to 2009 at 837 points [52]. The model developed by Tawa et al. [51] considers all weather conditions when estimating solar irradiation. The model of estimating the amount of agricultural production from solar irradiation was established in this study. Agricultural growth by photosynthesis is represented by the photosynthetic rate per leaf area (μmol-CO_2 m^{-2} s^{-1}) on the vertical axis and PPFD (μmol m^{-2} s^{-1}) on the horizontal axis. The reduction of PPFD and daily light integral (DLI) under solar panels was observed by Santra et al. [53]. We developed a model for calculating PPFD under solar panels from the amount of solar irradiation published in the METPV-11 solar irradiance database. This improved the accuracy of the modeling because the solar irradiance under the solar panels is lower than that above the solar panels, as shown in Figure 1 [50]. The amount of agricultural production was estimated from the PPFD calculated by solar irradiation.

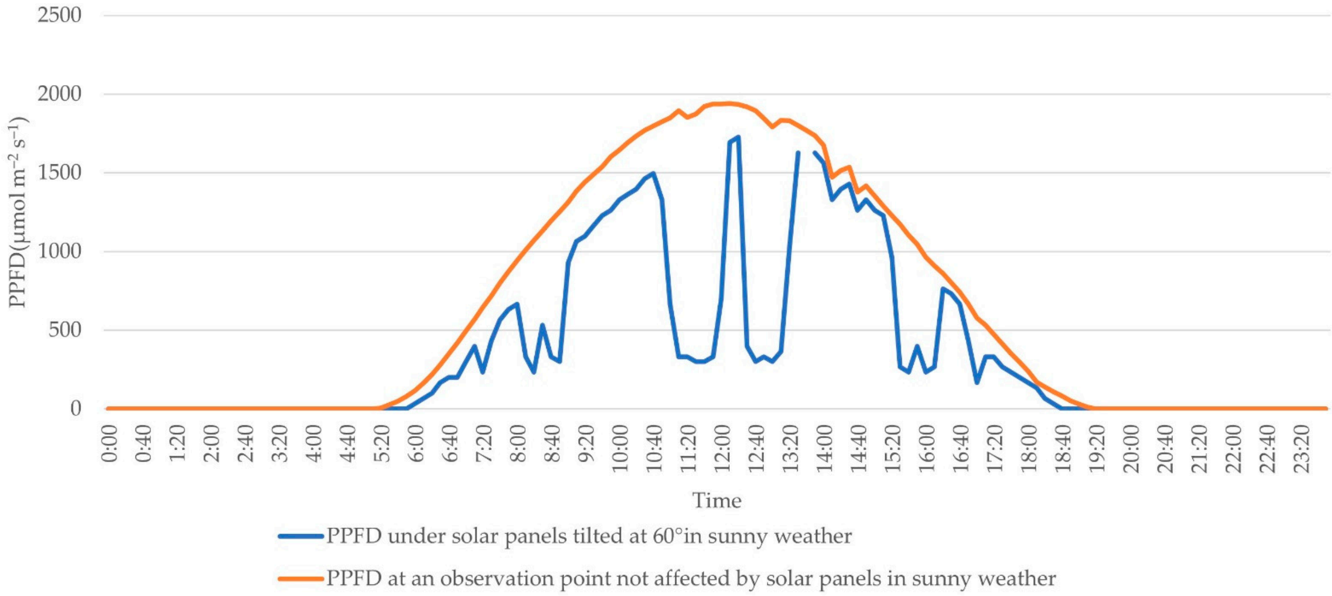

Figure 1. Difference in PPFD above and below solar panels. From Yajima et al. [50].

2. Materials and Methods

2.1. Materials

Cultivated plants suitable for the agrivoltaic system generally include shade plants and half-shade plants. However, non-shade plants (corn) have been examined in a system with raised installation heights of solar panels [54].

This study was conducted based on taro (*Colocasia esculenta* (L.) Schott) cultivation at the University of Miyazaki in Miyazaki Prefecture, as shown in Figure 2. Taro is a type of potato and is a half-shade plant with a relatively simple plant structure [55], and is often the subject of research on the effects of shading on plant growth.

Figure 2. Photo of agrivoltaic system (from Yajima et al. [50]).

The precondition for the calculations is included in Table 1 and the variables are defined in Table 2.

Table 1. Preconditions for the calculations.

Item	Precondition
Area of farmland	10,000 m^2
Installation rate of solar panels on the farmland	80% (8000 m^2)
Tilting angle of solar panels	30 degrees
Shading rate by solar panels	32.6%
Output of solar panel	218 Wm^{-2}
Unit selling price of electricity	10 yen kWh^{-1} (around USD0.09 kWh^{-1})

Table 2. Model variables.

Variables	Description
i	Index number of elapsed days from the start day of seed potato exposure to sunlight to the day of harvest ($0 \leq i < 170$)
W_p	Growth weight of child potatoes (g m^{-2} (farmland))
A_d	Photosynthetic rate per leaf area per day (μmol (CO_2) m^{-2} (leaf) d^{-1}, 0 <)
D_l	Leaf area per plant by elapsed days from the start day of seed potato exposure to sunlight (m^2 (leaf) per plant, 0 <)
W_d	Weight of carbon dioxide per mol (= 44.01 g mol^{-1} (CO_2))
R_m	Molecular weight ratio of carbon to carbon dioxide (= 12 / 44)
R_c	Carbon distribution rate to child potatoes by elapsed days (0 <)
R_t	Child potato's total carbon content rate (0 <)
W_c	Dry weight ratio of carbohydrates in child potatoes (= 0.131)
W_r	Dry weight ratio of protein in child potatoes (= 0.015)
W_f	Dry weight ratio of fat in child potatoes (= 0.001)
W_w	Weight rate other than water contained in child potatoes (= 0.159)
D_f	Farmland area per plant (m^2 (farmland) per plant) (0 <)

2.2. Growth of Taro

Germinated seed potatoes were planted in the field. The expansion of leaf area grown from seed potatoes accumulates nutrients in the potatoes to be harvested. The expansion of leaf area of taro is unaffected by shading [55]. The growth of its leaf area and carbon distribution to each organ by photosynthesis results from the elapsed days of growth inherent in the plant, regardless of the amount of solar irradiation. Therefore, this study established the model to estimate the growth of child potatoes as potatoes to be harvested based on the increase in carbon accumulation calculated from the amount of solar irradiation absorbed by increasing leaf area.

2.3. Growth Weight of Child Potatoes (W_p)

The child potato growth weight (W_p, g m^{-2} (farmland)) is the total daily growth beginning from the initial exposure of seed potatoes to sunlight to the day of harvest ($0 \leq i < 170$), according to following equation:

$$W_p = \sum_{i=1}^{n} S_i \tag{1}$$

$$S_i = \frac{A_d D_l W_d R_m R_c}{R_t W_w D_f} \tag{2}$$

The schema of above equation is shown in Figure 3:

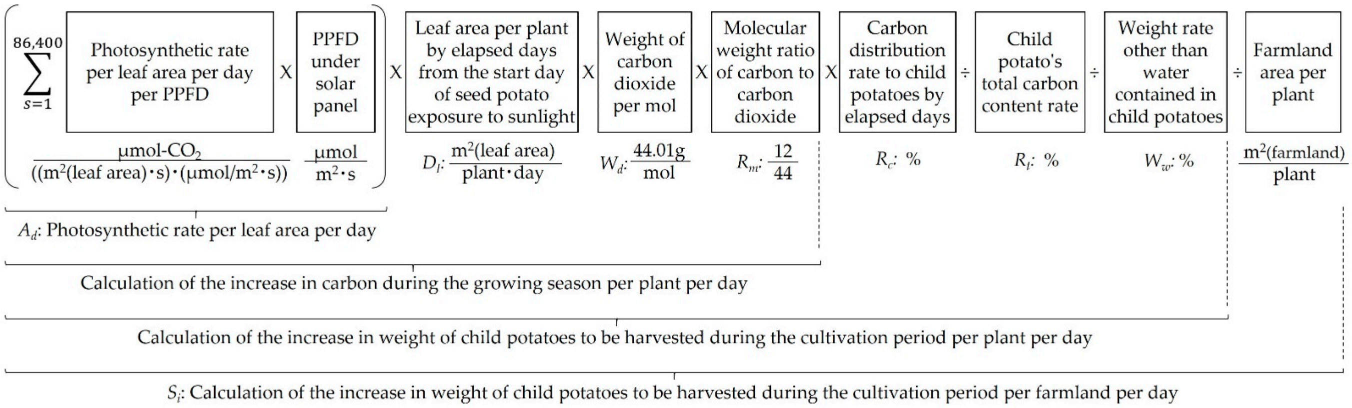

Figure 3. Schema of the equation.

where A_d (μmol(CO_2) m^{-2}(leaf) d-1, 0 <) is the photosynthesis rate per leaf area per day. This study used the formula of Sugimoto [56]. Sugimoto [56] derived the photosynthesis rate of the leaves of *C. esculenta* per leaf area per second (μmol (CO_2) m^{-2} (leaf) s^{-1}, 0 <) as the quadratic function of PPFD (μmol m^{-2} (farmland) s^{-1}, 0 <).

D_l (m^2 (leaf area) per plant, 0 <) is the leaf area per plant by elapsed days following exposure of the seed potatoes to sunlight. It was calculated based on the fact that the maximum individual leaf area of the whole taro plant occurs approximately 150 days after exposing seed potatoes to sunlight [55]. Sugimoto [57] summarized the changes in the photosynthetic product distribution of ^{13}C (carbon 13) with growth inferring the transition of the individual leaf area. The study did not describe when the seed potatoes were exposed to sunlight. On the other hand, a derivative study [56] described that "seed potatoes of each variety were exposed to sunlight on May 8, 1995, and. Seedlings with developed second to third leaves being were planted in a field converted from a paddy field in the Faculty of Agriculture, Ehime University, with a ridge of 90 cm and a stock spacing of 50 cm on June 16". Based on this description, the period from exposing seed potatoes to sunlight to the three-leaf development stage was estimated at 39 days. The same source describes that "one individual seedling of the three-leaf development stage of toba (a kind of taro) was transplanted to a 1/2000a Wagner pot on June 2, 1991". Based on this description, it was assumed that exposing seed potatoes to sunlight was implemented on April 24, 1991, subtracting 39 days from June 2, 1991.

In the present study, the dry weight (g/individual) of leaves was measured on June 18 before enlarging seed potatoes, on August 18 at the beginning of enlarging of grandchild potatoes grown further from the child potatoes to be harvested and September 19 at the beginning of enlarging of great-grandchildren. Dry matter weight increase and leaf area are proportional; the leaf area in total seed grown potatoes and child potatoes on the 150th day after exposing seed potatoes to sunlight is 8505 cm^2 [56]. The leaf area by elapsed day per plant after exposing the seed potatoes to sunlight was empirically represented using the 4-parameter logistics curve, which was created using three inflection points starting from zero, based on Sugimoto [56] (Figure 4).

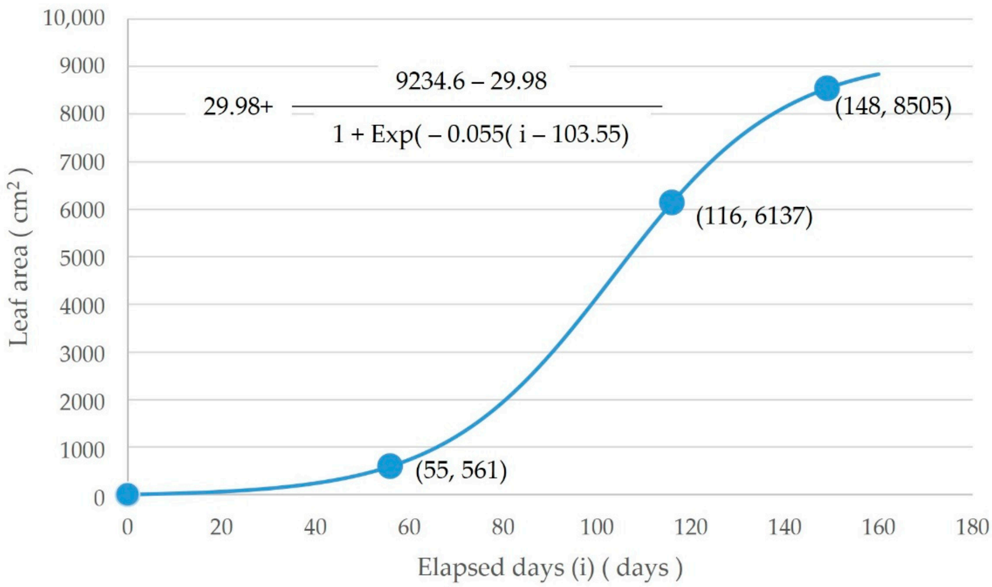

Figure 4. Elapsed day-to-day growth of leaf area starting from the exposure of seed potatoes to sunlight to the start of harvest (D_l).

W_d (0 <) is the weight of carbon dioxide per mol. This study set the W_d as 44.01g mol^{-1} (CO_2).

R_m (0 <) is the molecular weight ratio of carbon (12) to carbon dioxide (44).

R_c (0 <) is the carbon distribution rate to child potatoes by elapsed days. The growth-related changes in ^{13}C-photosynthetic product distribution in toba [57] did not describe the timing of exposing the seed potatoes to sunlight; therefore, the same method as the previous estimation of the leaf area per plant was adopted. This study assumed that the seed potatoes were exposed to sunlight on April 24, 1991. From the above assumptions, the change in the rate of carbon increases according to the growth of child potatoes was empirically represented by the 4 parameters of the Gompertz curve. Therefore, Figure 5 was created using three inflection points starting from zero, based on the method of Sugimoto [56]:

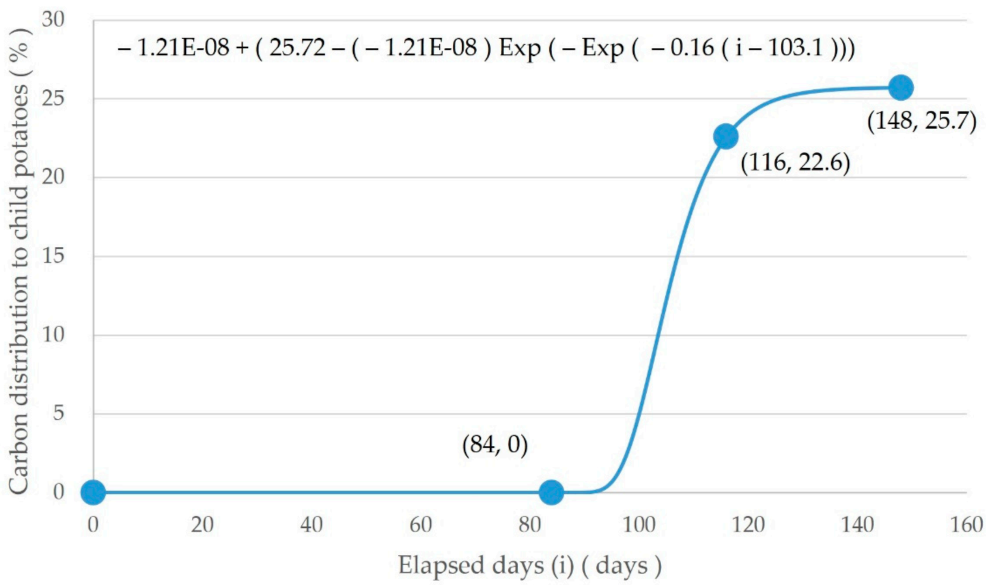

Figure 5. Carbon distribution rate to child potatoes by elapsed days (R_c).

R_t (0 <) is the child potato's total carbon content rate. The National Agriculture and Food Research Organization of Japan published the food composition table and the total carbon conversion formula based on the food composition table in Japan [58]. The total carbon conversion formula is as follows:

$$R_t = 0.44W_c + 0.53W_r + 0.77W_f \tag{3}$$

W_c (0 <) is the dry weight ratio of carbohydrates in child potatoes (0.13). W_r (0 <) is the dry weight ratio of protein in child potatoes (0.015). W_f (0 <) is the dry weight ratio of fat in child potatoes (0.0010). W_w (0 <) is the weight rate other than water in child potatoes (0.159) [58]. D_f (0 <) is the farmland area per plant. Taro cultivation is generally carried out with furrows of 90–100 cm and strains of 50 cm. This study set the farmland area per plant of 0.45 m^2 from 90 cm × 50 cm.

2.4. Model Verification

Model verification was carried out by comparing the past yield of taro in the Miyazaki Prefecture (published as statistical information) with the growing weight of child potatoes (Figure 6).

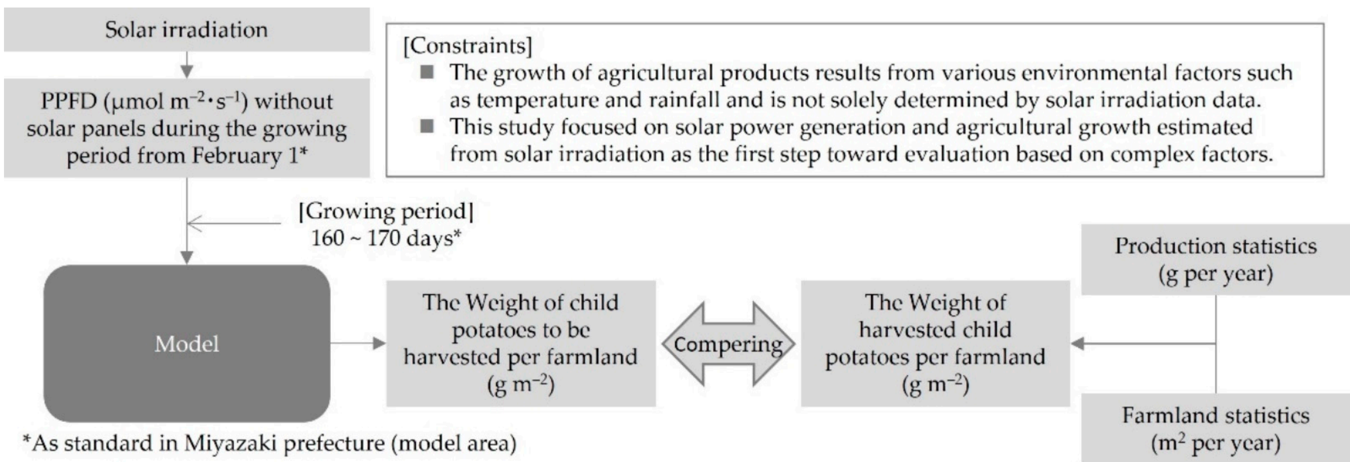

Figure 6. Methods for verifying model.

The taro yield was calculated by dividing the production volume (g) by the published farmland area (m^2). The growth weight of child potatoes used for comparison was calculated when solar panels were not installed on the farmland. Furthermore, since taro harvesting generally starts approximately 160 days after seed potato exposure to sunlight, child potato growth weight was calculated on the 160th day. The PPFD values used for the calculation was the average value for ten years in the Miyazaki Prefecture, calculated by Yajima et al. [50].

Using published statistical information, the five-year average yield of taro in the Miyazaki Prefecture from 2016 to 2020 was calculated as 1.288 kg m^{-2} and the ten-year average yield from 2011 to 2020 was calculated as 1.473 kg m^{-2} (Figure 7b).

The proposed model calculated the yield of child potatoes on the 160th day to be 1.296 kg m^{-2} and on the 170th day to be 1.570 kg m^{-2} (Figure 7a). The values calculated by the model were derived to have a difference of less than 1% from the average of the last 5 years calculated by the statistics.

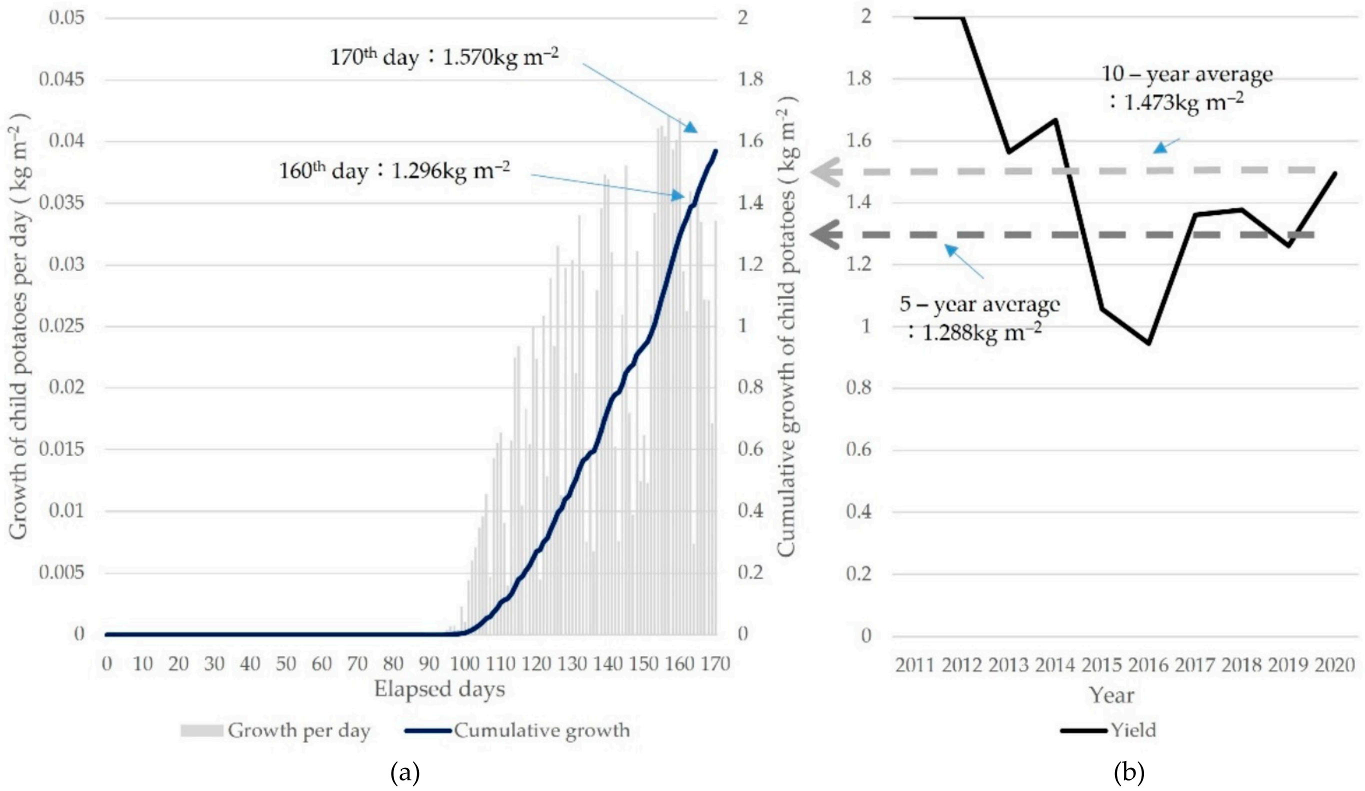

Figure 7. Comparison of taro yield using the model established by this study (**a**) and the actual yield in Miyazaki Prefecture (**b**).

3. Results

3.1. Impact of Solar Panel Installation on Crop Shipping Dates of Taro

The impact of solar panels installation on crop shipping time was quantified for three cases (Table 3).

Table 3. Three cases for qualifying impact of solar panels installation on crop shipping time.

Cases	Description
Case A	No solar panels installed
Case B	Highest calculated PPFD value on the farmland under the solar panels
Case C	Lowest calculated PPFD value on the farmland under the solar panels

In all cases, it was assumed that exposure of seed potatoes to sunlight was started on February 1, which was common in the Miyazaki Prefecture.

July 12 was the calculated date when child potato growth weight exceeded 1.3 kg m^{-2} (the standard weight for harvesting) in Case A. In comparison, the calculated harvest start date was delayed by 21 days to August 2 for Case B, and by 38 days (August 19) for Case C (Figure 8).

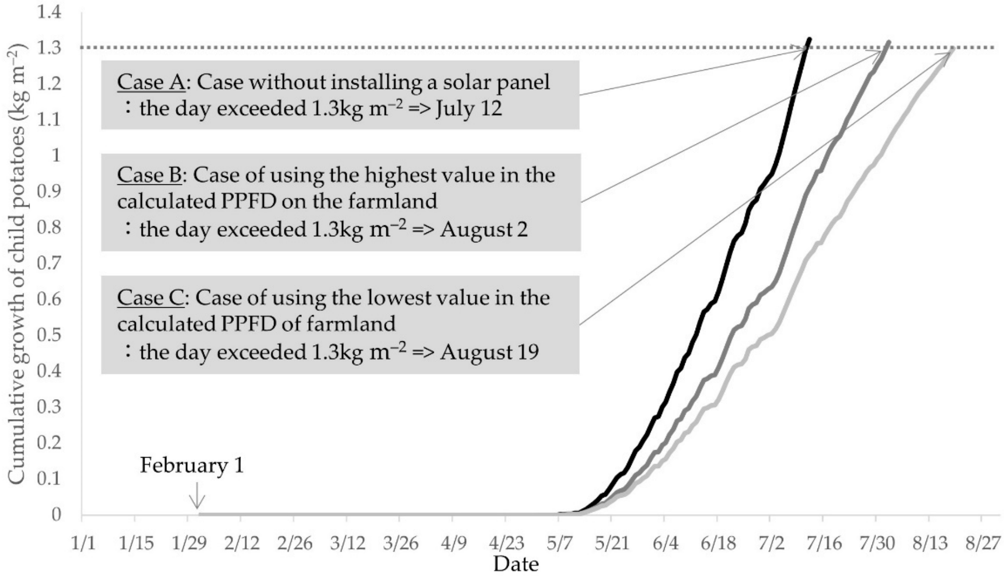

Figure 8. Impact of solar panel installation on taro shipping dates.

3.2. Calculation of Cultivation Date to Avoid Delaying Harvest Date Due to Solar Panel Installation

Although taro is consumed by households in Japan, high-end restaurants serve dishes containing taro all year round. As a result, wholesale prices increase in June and July when the supply falls (Figure 9). Farmers in Miyazaki Prefecture ship taro to target shortages and high wholesale prices.

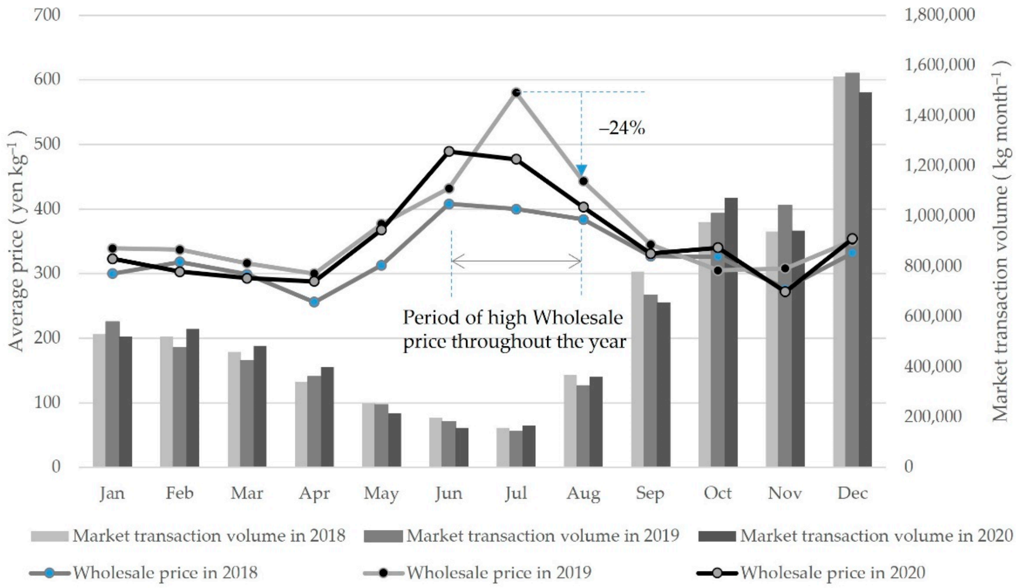

Figure 9. Monthly market transaction volume and average wholesale price of taro in the Tokyo Central Wholesale Market for the past three years (Adapted with permission from Ref. [59]. 2022, Metropolitan Central Wholesale Market of Japan).

The harvests start date for case A without installing a solar panel is on July 12. Aligning harvest date with Case A, the proposed model recommended bringing the start date of exposing the seed potatoes to sunlight forward from February 1 to January 9 for Case B (Figure 10). Although it is necessary to consider other environmental conditions and cultivation methods according to optimize the date of exposing the seed potatoes to sunlight, the model provides a useful guideline date.

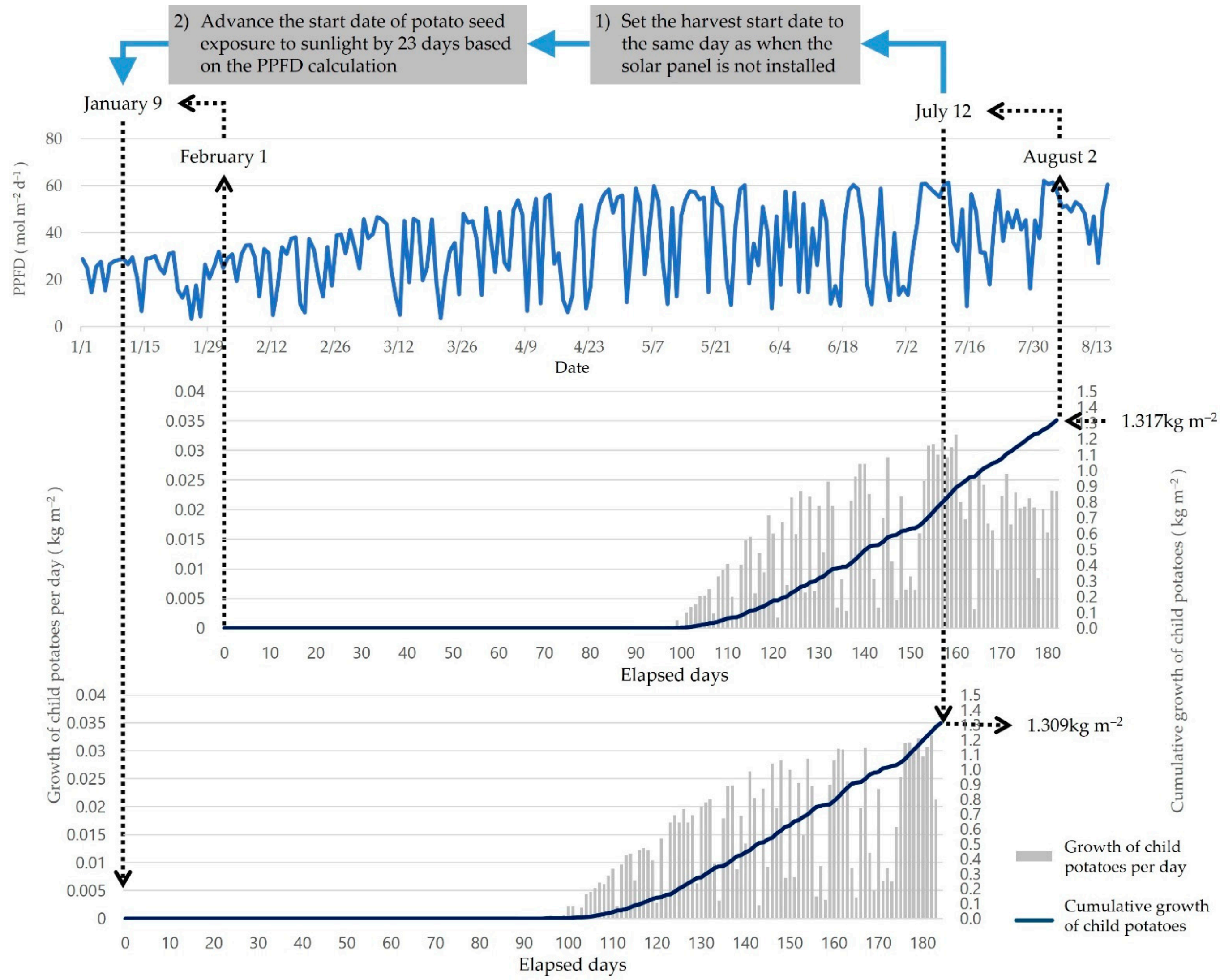

Figure 10. Calculation of cultivation date to avoid harvest date delays due to solar panel installation.

The amount of solar irradiation varies from year to year. If solar irradiation data in the whole year can be predicted based on data from the beginning of the year, this model could more accurately calculate the appropriate start date of exposing seed potatoes to sunlight according to the day which farmers want to start to harvest and ship.

4. Discussion

The wholesale price of taro in July 2019 was 580 yen kg^{-1} (around USD 5.1 kg^{-1}), compared to 443 yen kg^{-1} in August (around USD 3.9 kg^{-1}). Assuming a farmland area of 10,000 m^2, the difference in income between shipping in July and August is up to 1.8 million yen (approximately USD 16,000). Therefore, delays in shipping can significantly impact farmers' income.

One possible method to increase farmers' income while maintaining agricultural production for increasing food demand is to change the shading rate of the solar panels to maximize power generation. This involves covering the entire farmland with solar panels when the land is unsuitable for cultivation and reducing the number of installed solar panels during the cultivation of agricultural products to secure the amount of solar irradiation required for product growth.

Based on the results in Figure 10, the following preconditions are added to Table 1 (Table 4).

Table 4. Preconditions for discussion added to Table 1.

Item	Precondition
Seed potatoes sunlight exposure date	January 9
Harvest starts data	July 12 and continues for two months
Shading rate during cultivation	32.6%
Shading rate when cultivation is unsuitable	100%

The results are presented in Figure 11.

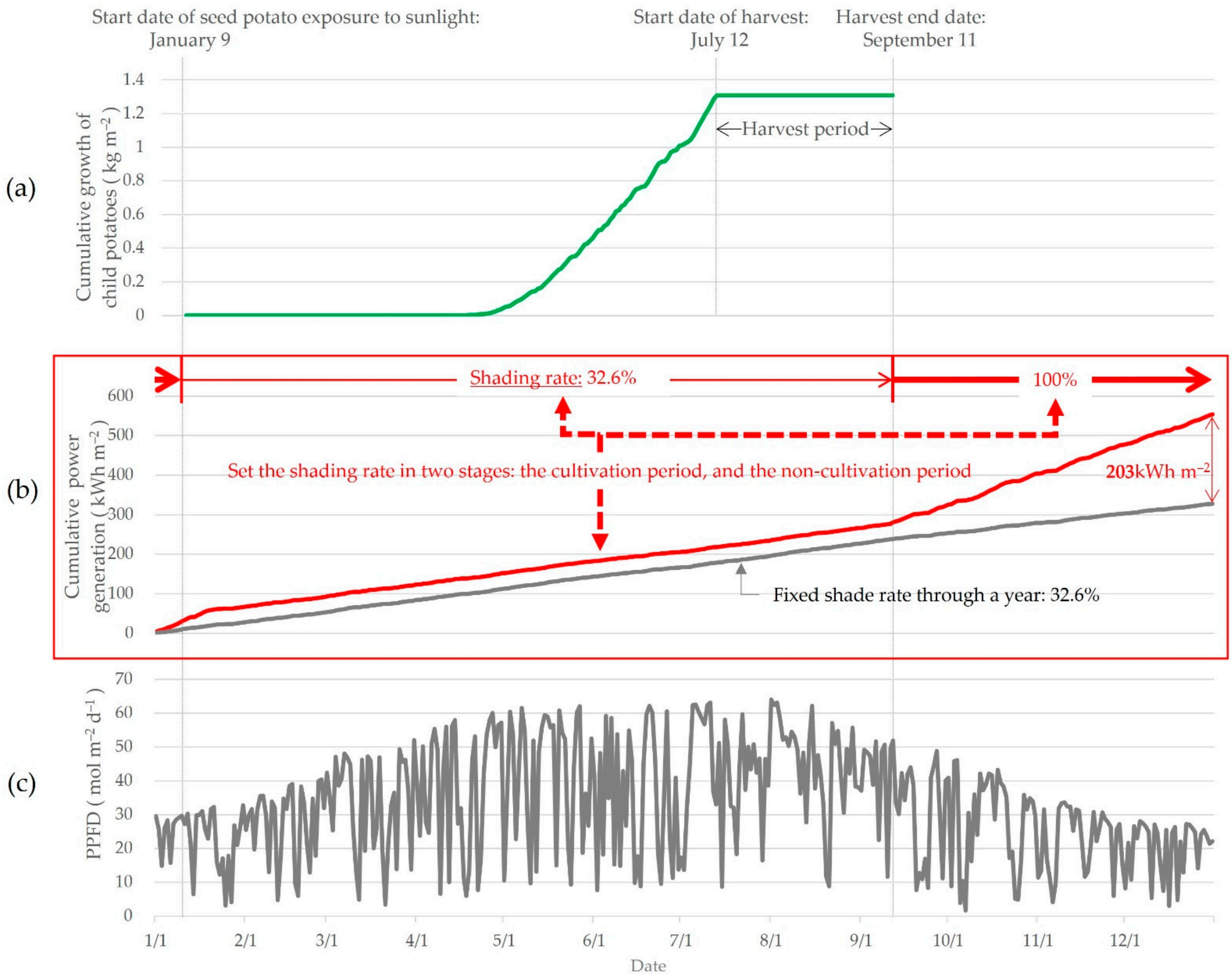

Figure 11. Difference in cumulative power generation for different shading rates set depending on growing conditions (**b**), cumulative growth of child potatoes (**a**), and PPFD changes (**c**).

Based on Figure 11, farmers start to expose the seed potatoes to sunlight on January 9 to ship taro in July, when the highest wholesale prices are expected. When the harvest ends on September 11, the shading rate is 32.6%. At the end of the harvest, the farmer spreads solar panels over the entire farmland and sets the shading rate to 100%. This shading rate is maintained until the start of cultivation the following year.

The additional power generation gained by changing the shading rate according to the stage was calculated at 203 kWh m^{-2} for 10,000 m^2 of farmland. This economic value amounted to 16.2 million yen (approximately USD 142,000) per year. Depending on the cost associated with solar panel relocation (including labor costs), there is a considerable profit to farmers (Figure 11). A summary of the values estimated by the model for 10,000 m^2 of farmland is provided in Figure 12.

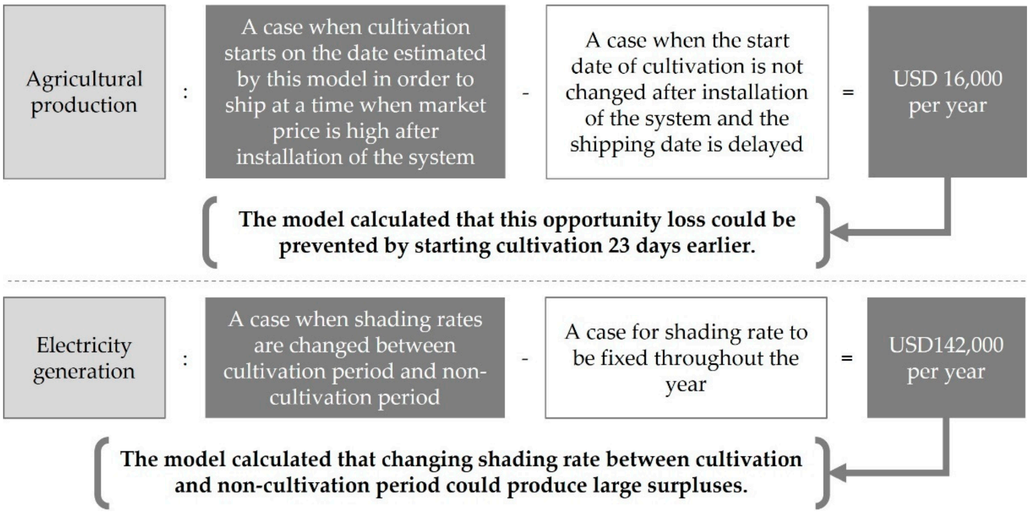

Figure 12. Summary of values estimated by the model.

4.1. Model Applicability

The installation of agrivoltaic systems is declining in Japan due to the falling sale prices of electricity generated by solar power and the negative impacts of solar panel installation on agricultural growth. However, many places in the world are under increasing pressure to meet energy and food demands with a limited amount of land. Therefore, effective use of land in a coordinated manner through combining its uses are indispensable. Solar panel performance and durability have improved due to technological advances and prices have declined. Therefore, their utility as a tool for use in sharing purposes is increasing.

The advantage of this model is that the amount of renewable power generation and agricultural production by the introduction of the agrivoltaic system can be calculated using a single variable, solar irradiation. With this model, farmers could estimate the benefit of the system in advance by simply obtaining solar irradiation data for the target area. This simplified model is an effective tool for farmers who have long experience in the target area and can empirically predict the impact of environmental and weather changes on agricultural output. On the other hand, the model, which does not consider environmental and weather impacts, may mislead farmers and investors who are inexperienced in the target area. To promote the agrivoltaic system, it is essential to develop tools that can be used by farmers and investors unfamiliar with the target area. Improving model performance is vital for this and could be achieved by incorporating environmental and weather factors. One method is to use dummy variables to incorporate environmental and weather effects into the equation. Another method is to reflect environmental and weather effects in the PPFD calculated from solar irradiation.

The growth associated with photosynthesis of various agricultural products has been the subject of research in many agronomic papers. Using this model, the impact of the introduction of agrivoltaic systems on the production of other agricultural products can be quantified by applying other variables such as photosynthetic rate and carbon distribution rate to the harvested object for the target agricultural product-specific numerical information.

4.2. Study Limitations and Future Study

The growth of agricultural products depends on various environmental factors, such as temperature and rainfall, and is not solely determined by solar irradiation. Therefore, this study focused on photovoltaic electricity generation and agricultural growth estimated from solar irradiation as a first step towards a more comprehensive evaluation based on complex factors. Some studies have used artificial intelligence models to predict the performance of equipment from multiple input variables. For example, Almodfer et al. [60] conducted performance prediction of a solar-powered thermoelectric air-conditioning system using advanced optimized artificial intelligence models. Establishing models from various environmental variables by utilizing these advanced methods is a subject for further study.

5. Conclusions

To introduce the agrivoltaic system, farmers must bear the high initial and maintenance costs of the system. This study established a model that calculates the quantitative effect of the introducing the system in any area with solar irradiation data based on taro cultivation in Miyazaki Prefecture as a model case. This model can predict the power generated, production of agricultural products, and the ideal cultivation start date, which allows farmers to develop a concrete business strategy to assess feasibility of introducing the system. The proposed model could encourage farmers to change their behavior by quantifying the reduction in agricultural production and producer surplus created by the introduction of the agrivoltaic system.

Power generation using solar panels is commonplace on the roof area of residential houses and factories. We hope that the land will continue to be shared to generate renewable energy and produce agricultural products in a coordinated manner in the future.

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