INTRODUCTION

Due to a growing human population and the concomitant increased demand for resources, the simultaneous production of sufficient food and energy while also preserving the environment. Both agricultural production for food generation and photovoltaics for renewable energy production require large, open fields. In this research study, we investigate the feasibility of combining food and energy production into a single field by examining the effects of installing photovoltaic equipment above land used for farming. We grew komatsuna, kabu, mizuna, and spinach underneath photovoltaic equipment, and investigated the influence of shading from the photovoltaic equipment on plant growth and yields during winter cultivation. As expected, both the amount of solar radiation and the air and soil temperature were lower under the photovoltaics than those under the open field. The growth rate of komatsuna, kabu, and mizuna were slower. However, yields and qualities sufficient to meet market demands remained possible with extension of the cultivation periods. Therefore, although temperature and solar radiation are reduced under the photovoltaic equipment in winter, it is nevertheless possible to produce vegetables in the farmland, providing a novel opportunity to realize an integrated agricultural system with parallel production of food and energy.

Keywords: photovoltaic systems, shade, komatsuna, mizuna, kabu, spinach

Effects of Agrivoltaics (Photovoltaic Power Generation Facilities on Farmland) on Growing Condition and Yield of Komatsuna, Mizuna, Kabu, and Spinach

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MATERIALS AND METHODS

Photovoltaic power generation system

Between November 2014 and March 2015 we carried out experiments using an agrivoltaic system (Looop Inc., Tokyo, Japan) (Fig. 1) at the University of Miyazaki, Japan (31°8’N, 131°41’E).

The system comprised 112 photovoltaic panels (PVPs), with an electricity generating capacity of 100 Wp per panel. The size of the PVP was 1.2×0.54 m, with a total electricity generating capacity of 11.2 kWp. In order to enable mechanical plowing and harvesting of the plants with tractors, we positioned the PVPs 3 m above the ground using steel pillars spaced on a 10.8×10.8 m square grid (Fig. 1A, B, D). Set horizontally, the PVPs covered 62% of the ground area of the farm.

Our experimental design comprised two full sun controls and two experimental treatments that varied the shade intensity due to different tilts of the PVP arrays. For the constant tilt treatment (CT), we included a constant tilt for the PVPs with a fixed horizontal angle for the panel, achieving in 38% transmission of incident radiation available to the crops at noon (Fig. 1B, E). The tracking treatment (TT) involved single-axis trackers changed monthly to account for variation in the sun’s altitude (November: 50°, December: 60°, January: 55°, February: 50°, and March: 30°) (Table 1, Fig. 1C, F). This tilting produced the optimal PVP density for electricity production and transmitted 11% of the incident radiation available to the crops at noon. The full sun control was not shaded by PVPs and thus transmitted 100% of incident radiation to the crops.

Microclimate monitoring

We measured incident global solar radiation 1.2 m above the ground every 10 min in each treatment using silicon-cell pyranometers (CAP-SP-110, Apogee Instruments, Inc., Logan, UT, USA) connected to data loggers (CR1000, Campbell Scientific Inc., Logan, UT, USA). We calculated the total integrated solar radiation from the incident global solar radiation data. In addition, we measured the air temperature every 10 min 1.2 m above the ground from November 29, 2014, to February 1, 2015, and monitored the soil temperature 10 cm below the ground using T-type thin thermocouples.

Plant materials and growth conditions

We sowed seeds of spinach mustard (komatsuna) (Brassica rapa L. var. Perviridis Group cv. Natsurakuten), potherb mustard (mizuna) (Brassica rapa L. Japonica Group cv. Kyoshigure), Japanese small turnip (kabu) (Brassica rapa L. Rapifera Group cv. CR Yukibana), and spinach (Spinacia oleracea L. cv. Bentenmaru) on single north–south oriented ridges on November 11th, 2014. The ridge width was 0.9 m and the furrow width was 0.45 m. We planted the four species separately, but on adjacent sites. We planted each crop in three rows with 0.30 m spacing. We planted the komatsuna, mizuna, kabu, and spinach on the rows at distances of 0.05 m, 0.15 m, 0.15 m, and 0.05 m, respectively. We did not use plastic mulching film, and grew all crops on bare soil. We fertilized plants based on a soil nutrient element analysis, applying fertilizer before seeding at the following nutrient concentrations: 140 kg N ha⁻¹, 140 kg P₂O₅ ha⁻¹, and 140 kg K₂O ha⁻¹ using granular fertilizer (NPK fertilizer, 8-8-8). This ensured that nutrients were not a limiting factor for plant growth in any treatment.

| Table 1 | Tilt angle of panels and date of adjustment |
|---------|-------------------------------------------|
|          | Constant tilt treatment                   | Tracking treatment                  |
| Adjusted date | Adjusted tilt (°) | Optimum tilt (°) | Adjusted tilt (°) |
| Nov. 11, 2014  | 0 | 52.0 | 50 |
| Dec. 17, 2014  | 0 | 58.7 | 60 |
| Jan. 8, 2015   | 0 | 56.4 | 60 |
| Feb. 5, 2015   | 0 | 46.4 | 50 |
| Mar. 1, 2015   | 0 | 31.5 | 30 |

Optimum tilts followed the “MONSOLA-11” (NEDO, New Energy and Industrial Technology Development Organization, Japan) database. https://www.nedo.go.jp/library/nissharyou.html (Accessed 11 March 2021).
Plant harvest and measurement of growth parameters

We harvested komatsuna plants 70, 95, and 110 days after sowing (DAS), mizuna plants 73, 103, and 113 DAS, kabu plants 96, 105, and 114 DAS, and spinach plants only once (108 DAS) due to their slow growth rate. The first harvest occurred when we harvested each crop in the control plots according to its commercial harvest maturity stage. We randomly picked plants of each crop in each condition at each sampling date.

We measured seedling fresh weight (FW) and harvest dates according to the schedule shown in Table 2. We measured FW of shoots and plant height at the first, second, and third harvest, and FW of roots only for kabu. We estimated the number of days that it took plants in the experimental treatments to reach the FW of the first harvest in the control from the regression of FW on DAS. We determined regression equations for FW for each crop by estimating DAS when FW of the TT and the CT plants reached that of the control plants. We estimated relative chlorophyll content (SPAD index) using a portable chlorophyll meter (SPAD-302Plus; KONICA MINOLTA JAPAN, Inc., Tokyo, Japan) on February 27, 2015.

We measured maximum photochemical quantum yields of photosystem II (PSII) (Fv/Fm = \( \Phi_P \)) on leaves of all plants. Before measurement, we equipped leaves with special plastic clips for a 30-min dark treatment (provided by Opti-science, Inc., NH, USA). We measured Fv/Fm using a portable chlorophyll a fluorometer (OS-30p; Opti-science, Inc., NH, USA), and carried out measurements on the adaxial leaf lamina on February 27, 2015.

Relative solar radiation use efficiency (RSRUE)

We calculated the relative solar radiation use efficiency (RSRUE) to investigate the relationship between solar radiation intensity and FW. RSRUE was calculated as the ratio of the TT or CT value to the control value by calculating the FW per integrated solar radiation with reference to the radiation use efficiency (RUE) (Tei et al., 1996; Rizzalli et al., 2002), which represents the dry weight (DW) per integrated solar radiation, as follows:

\[
RSRUE = \frac{FW_{TT or CT} / SR_{TT or CT}}{(FW_{control} / SR_{control})}
\]

where \( FW_{TT or CT} \) and \( FW_{control} \) were FW in the TT or CT and the control, and \( SR_{TT or CT} \) and \( SR_{control} \) were the integrated solar radiations from sowing date to each harvest date in the TT or CT and the control.

Economic assessment

The cultivation density per system area was 5,184 plants for komatsuna and spinach, and 1,728 plants for mizuna and kabu. The yield was calculated by multiplying the number of plants by the FW. The power generation per system was calculated by integrating the power generation from the sowing date to each harvest date. The power sales income was calculated at the power sales price of 37 yen/kWh. The income from crop sales was calculated based on the daily wholesale market price of the fruits and vegetables according to the survey conducted by the Ministry of Agriculture, Forestry and Fisheries. The market price on the day after the harvest date was used for the calculation; however, if the data were unavailable, the market price on the day after the next day was used. Since market price data for mizuna and kabu shoots were not available, the prices of “other vegetables” were used. Finally, the total income was calculated by adding the income from the crop sales and that from the electricity sales.

Statistical analysis

We conducted statistical analysis using BellCurve for Excel Ver. 2.11 (Social Survey Research Information Co., Ltd., Tokyo, Japan) to determine the significance of the effects of the shading treatments by photovoltaic panels on plant height and FW by Tukey–Kramer’s test at \( P < 0.05 \).

RESULTS

Microclimate conditions

The shade of the PVPs and frames caused low levels of hourly incident radiation in the TT and CT plots (Fig. 2A). The peaks of radiation in the TT, CT, and control plots were 0.5, 1.7, and 2.4 MJ m\(^{-2}\)h\(^{-1}\), respectively. Integrated solar radiations transmitted below the PVPs during the growing season in the TT and CT plots were 24% and 39% of that measured in the control plots, respectively (Fig. 2B). The average daily incident global solar radiation values in the TT, CT, and control plots were 2.6, 4.4, and 11.1 MJ m\(^{-2}\)d\(^{-1}\), respectively.

The mean daily air temperature was highest in the control plots at 8.1 °C and lowest in the TT plots at 7.8 °C. The TT and CT plots were less influenced by shade treatment (Fig. 3A). The mean daily maximum and minimum temperatures during the experiment were 13.7 °C and 3.5 °C, respectively, in the control plots (Fig. 3B, C). The mean daily minimum temperature during the cultivation period was lowest for the control plots at 3.5 °C, followed by that in the TT plots at 3.6 °C and CT plots at 3.7 °C (Fig. 3C). The mean diurnal air temperature range was largest in the control plots at 10.2 °C and lowest in the TT plots at 9.0 °C (Fig. 3D). Soil temperature was reduced in the shade. In particular, the minimum soil temperature in the TT plots was lower by approximately 2 °C than that of both the CT and control plots (Fig. 4).

### Table 2: Date of seed sowing and measurement of fresh weight.

| Crop      | Sowing | Seedling | First harvest | Second harvest | Third harvest |
|-----------|--------|----------|---------------|----------------|--------------|
| Komatsuna | Nov. 11| Dec. 27 (46) | Jan. 20 (70) | Feb. 24 (95) | Mar. 1 (110) |
| Mizuna    | Nov. 11| Jan. 3 (53)  | Jan. 23 (73) | Feb. 22 (103) | Mar. 4 (113) |
| Kabu      | Nov. 11| Jan. 3 (53)  | Feb. 5 (86)  | Feb. 24 (105) | Mar. 5 (114) |
| Spinach   | Nov. 11| Feb. 5 (86)  | Feb. 27 (108) |               |              |

*Numbers in parentheses indicate days after sowing.*

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Plant growth and yield of komatsuna

In the TT and CT treatments, the FW of seedlings 46 days after sowing were reduced significantly compared to that of the controls (17% and 29% respectively; Fig. 5A). The shoot FW at the first, second, and third harvest were reduced significantly compared with that of the controls in both the TT (22%, 14%, and 34%, respectively; Fig. 5B) and the CT treatments (19%, 25%, and 50%, respectively; Fig. 5B). The greater shading resulted in slower growth, but there was no significant difference between the TT and the CT. Although growth in both the TT and the CT was delayed compared to that in the controls, the FW of the experimental treatments 110 DAS was equal to or greater than that of the controls at 70 DAS (Fig. 5B). Calculating by regression equations, we determined that for the FW of the TT and the CT plants, respectively, to reach the same
level as that of the first harvest of control plants took 110 and 102 days, respectively—corresponding to a 40 and 32 day delay (Fig. 5B).

At 70 DAS, the plant height of the control plants—ranging between 20 and 30 cm—met the shipment standard for the Japanese vegetable market. Neither the TT nor the CT plants, however, reached this size until 95 DAS (Fig. 5C). We measured the significantly reduced plant heights at the first, second, and third harvest relative to those of the controls in both the TT (55%, 58%, and 63%, respectively) and the CT (60%, 77%, and 79%, respectively). At 95 and 100 DAS, the plant heights were significantly different among all treatments. The ratios of plant heights of the TT and the CT to the control were higher than the ratios of shoot FW. In addition, the ratio of plant height to FW was greater in the TT plots with lower solar radiation [1.85 (63%/34%)] than in the CT plots [1.58 (79%/50%)] at 100 DAS. We infer that low light conditions made the komatsuna spindly.

In all treatments, the SPAD value was highest in the control plants but among the other treatments there was no significant difference between treatments (Table 3). We measured maximum photochemical quantum yield (Fv/Fm) as an indicator of environmental stress, including heat and chilling (Adams and Demming-Adams, 2004), and found the Fv/Fm values to be lower in the control plants than those of the TT, because of the shade conditions generated by the panels (Table 3).

**Plant growth and yield of mizuna**

In both the TT and the CT treatments, the FW of seedlings 53 days after sowing were reduced significantly (4% and 15% of control FW, respectively; Fig. 6A). At the first,
second, and third harvest, the shoot FW was reduced significantly compared to that of the controls in both the TT (22%, 31%, and 53%, respectively) and the CT treatments (22%, 59%, and 135%, respectively; Fig. 6B). The greater shading resulted in slower growth, but there was no significant difference between the TT and the CT. Although growth of the TT and the CT were delayed compared with that of the control, the FW of both the TT and the CT plants at 103 DAS was equal to or greater than that of the control plants at 73 DAS. The FW of the TT and the CT plants took 100 and 86 days, respectively, to reach the same level as that of the first harvest of control plants, corresponding to a 27 and 13 day delay (Fig. 6B).

At 73 DAS, the plant height of the control plants ranged between 25 and 45 cm, which met the shipment standard for the Japanese vegetable market. The plants in the TT and CT treatments reached this height at 73 DAS and 103 DAS, respectively (Fig. 6C). The plant heights at the first, second, and third harvest were reduced significantly compared to controls in both the TT (60%, 87%, and 89%, respectively) and the CT treatments (82%, 96%, and 91%, respectively). The plant heights were significantly different among all treatments at 73 DAS. The ratios of plant heights of the TT and the CT to the control were greater than the equivalent ratios of shoot FW. Because the majority of plants under all conditions were bolting at 113 DAS, these plants had almost no value at the market.

The SPAD and Fv/Fm values were similar under all conditions (Table 3). The plant height of the control plants ranged between 25 and 45 cm, which met the shipment standard for the Japanese vegetable market. The plants in the TT and CT treatments reached this height at 73 DAS and 103 DAS, respectively (Fig. 6C). The plant heights at the first, second, and third harvest were reduced significantly compared to controls in both the TT (60%, 87%, and 89%, respectively) and the CT treatments (82%, 96%, and 91%, respectively). The plant heights were significantly different among all treatments at 73 DAS. The ratios of plant heights of the TT and the CT to the control were greater than the equivalent ratios of shoot FW. Because the majority of plants under all conditions were bolting at 113 DAS, these plants had almost no value at the market.

The SPAD and Fv/Fm values were similar under all conditions (Table 3).
conditions, and there was no significant difference among treatments (Table 3).

**Plant growth and yield of kabu**

At 53 DAS the FW of seedlings was reduced significantly in both the TT and the CT treatments (22% and 30% of the control, respectively; Fig. 7A). The shoot FW at the first, second, and third harvest was reduced significantly compared to that of the controls in both the TT (66%, 70%, and 63%, respectively) and the CT treatments (68%, 71%, and 55%, respectively; Fig. 7B). The greater shading resulted in slower growth, but there was no significant difference between the TT and the CT. Although the growth of both was delayed compared to the controls, the shoot FW of the TT and the CT plants at 105 DAS was equal to or greater than that of the FW of the control plants at 86 DAS. It took 101 and 99 days for the shoot FW of the TT and the CT plants to reach the same level as that of the first harvest of the control plants, corresponding to a 15 and 13 day delay, respectively (Fig. 7B). In addition, the plants in the experimental treatments reached the same root FW as that of the control’s first harvest plants at 103 and 98 days, which corresponded to a 17 and 12 day delay (Fig. 7C).

At 86 DAS, the spherical diameter of the control plants reached 5 cm, which met the shipment standard for the Japanese vegetable market. However, plants in the TT and the CT treatments reached this spherical diameter only at 105 DAS. The root FW at the first, second, and third harvest was reduced significantly compared to that of the controls in both the TT (45%, 41%, and 44%, respectively) and the CT treatments (46%, 51%, and 42%, respectively; Fig. 7C). The greater shading resulted in slower growth, but there was no significant difference between the TT and the CT. Although the growth of these two treatments was delayed compared to that of the controls, the root FW of the TT and the CT plants at 105 DAS was equal to or greater than the FW of the control plants at 86 DAS.

The plant heights at the first, second, and third harvest were reduced compared to the controls in both the TT (82%, 87%, and 96%, respectively) and the CT treatments (84%, 92%, and 94%, respectively; Fig. 7D). The plant heights were significantly different among all treatments at 86 DAS. The ratios of plant heights of the TT and the CT to the control plants were higher than the ratios of shoot and root FW.

The SPAD value for the TT plants was significantly higher than that for the control plants, but there was no significant difference between that for the CT and that for other conditions (Table 3). Although the Fv/Fm value was
higher for the TT than for the CT or the control, there was no significant difference among the three conditions (Table 3).

**Plant growth and yield of spinach**

The FW of seedlings and shoots of both the TT and the CT plants were reduced significantly compared to those of the controls (14% and 18% at 86 DAS, respectively, and 4% and 18% at 108 DAS, respectively; Fig. 8A, B). At 108 DAS, the plant height in the control plants ranged between 15 and 35 cm (Fig. 8C), which met the shipment standard for the Japanese vegetable market. However, plants in the TT and the CT treatments did not reach this height until 124 DAS. As a consequence of this extensive delay, we did not measure SPAD and Fv/Fm in the spinach plants.

**Relative solar radiation use efficiency (RSRUE)**

The early growth rate of komatsuna in the control plots was high, and the RSRUE of komatsuna in the TT
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Table 4 Effect of shading treatments by photovoltaic panels on crop income, power generation income, and total income.

| Crop  | Number of harvests | Crop sales income (yen/system) | Electricity sales income (yen/system) | Total income (yen/system) |
|-------|--------------------|-------------------------------|--------------------------------------|--------------------------|
|       |                    | TT                            | CT                                   | Control                  |
|       |                    | TT                            | CT                                   | TT                       | CT                       | Control                  |
| Komatsuna | 1st | 469          | 43,778                        | 37,962                               | 202,471                  | 109,349                  | 100,127                  | 117,152                  | 202,471                  |
|         | 2nd | 431          | 66,783                        | 113,047                              | 461,230                  | 132,996                  | 98,857                   | 199,780                  | 461,230                  |
|         | 3rd | 329          | 139,806                       | 206,206                              | 411,041                  | 167,851                  | 131,987                  | 307,658                  | 338,193                  | 411,041                  |
| Mizuna  | 1st | 441          | 6,416                         | 6,320                                | 28,710                   | 112,241                  | 81,956                   | 118,678                  | 88,276                   | 28,710                   |
|         | 2nd | 412          | 28,714                        | 54,668                               | 92,761                   | 156,466                  | 121,125                  | 185,179                  | 175,793                  | 92,761                   |
|         | 3rd | 320          | 25,738                        | 65,068                               | 48,353                   | 174,093                  | 138,238                  | 199,831                  | 283,306                  | 48,353                   |
| Kabu shoot | 1st | 437          | 22,257                        | 22,864                               | 33,690                   | 134,150                  | 100,041                  | 156,387                  | 122,905                  | 33,690                   |
|         | 2nd | 366          | 31,090                        | 31,937                               | 44,528                   | 158,591                  | 123,267                  | 189,681                  | 155,204                  | 44,528                   |
|         | 3rd | 309          | 30,828                        | 26,890                               | 49,057                   | 174,280                  | 138,416                  | 205,108                  | 165,326                  | 49,057                   |
| Kabu root | 1st | 126          | 5,940                         | 6,053                                | 11,085                   | 134,150                  | 100,041                  | 140,070                  | 106,095                  | 11,085                   |
|         | 2nd | 144          | 15,728                        | 19,596                               | 38,598                   | 158,591                  | 123,267                  | 174,319                  | 142,863                  | 38,598                   |
|         | 3rd | 141          | 22,574                        | 21,105                               | 50,747                   | 174,280                  | 138,416                  | 196,855                  | 159,541                  | 50,747                   |
| Spinach | 1st | 443          | 2,457                         | 12,975                               | 0.080                    | 162,348                  | 126,846                  | 164,805                  | 139,821                  | 70,080                   |

Market prices according to the “Ministry of Agriculture, Forestry and Fisheries Wholesale Market Survey of Fruits and Vegetables (Daily Survey).”
https://www.maff.go.jp/j/tokuryou/seika_orosi/ (Accessed 11 March 2021).

DISCUSSION

Here, we investigated the influence of shade from photovoltaic panels (PVPs) located 3 m above farmland on the yield and growth of several vegetable crops. Other than the daily minimum air and soil temperatures, the air temperature parameters were higher with more solar radiation. For example, the mean daily minimum air temperature during the cultivation period was higher in the TT plots and highest in the CT plots than in the control plots (Fig. 3C). However, based on the three-square theorem, if the ratio of the ground coverage by the panels in the CT plots with a horizontal panel angle was 1, and the ratio of the ground coverage by the panels of the TT plots with a 60° panel angle was 0.5, then the coverage ratio was greater in the CT plots than in the TT plots. Therefore, the installation of solar panels was effective in reducing radiative cooling during the night. Moreover, the effect was greater with higher coverage.

We inferred that low light conditions made komatsuna, mizuna, and kabu spindly (Figs. 5A, 6A, 7A, Table 3). Yield, light intensity, air temperature, and soil temperature decreased beneath the PVPs compared to those under the no shade condition, particularly for yield in spinach (Fig. 8B). Plant weight was influenced by light intensity, and in regions of higher shading, growth rate was reduced more substantially (Fig. 8B), as observed previously (Fallovo et al., 2009; Dupraz et al., 2011; Stagnari et al., 2015; Tani et al., 2014). The yields of the other three crops when shaded by the PVPs were, however, comparable to the first harvest yield in the no shade condition (Figs. 5B, 6B, 7B, C). Thus, even with the slower growth of crops in response to shading, we were able to increase yields by extending the cultivation periods, a result that has been described previously in other studies (Kadowaki et al., 2012).

We suggest that the lower RSRUE during the early growth stages of komatsuna, mizuna, and spinach could be attributed to lower solar radiation intensity, lower plant size (leaf area index), and lower temperatures in the winter (Andrade et al., 1993; Tei et al., 1996; Rizzalli et al., 2002; Francescangeli et al., 2006). The RSRUE of kabu—apart from the shoots and roots—was lower than that of komatsuna and mizuna (Table 4). The maximum total income of komatsuna was 307,658 yen at the third harvest in the TT plots. The maximum income of mizuna was 203,306 yen at the third harvest in the TT plots. The maximum income of kabu shoots was 227,683 yen at the third harvest in the TT plots. The maximum income of spinach was 164,805 yen, but the size of the crop under the PVPs did not meet the shipping standard. As a result, the maximum total income of komatsuna was 461,230 yen at the second harvest control, but the plant height exceeded the shipment standard (Fig. 5C). As a result, the maximum total income of komatsuna within the shipment standard was 307,658 yen at the third harvest in the TT plots. The maximum total income of kabu shoots was 227,683 yen at the third harvest in the TT plots. The maximum income of spinach was 164,805 yen at the third harvest in the TT plots. The maximum income of mizuna was 156,466 yen at the third harvest in the TT plots. The maximum income of komatsuna was 307,658 yen at the third harvest in the TT plots. The maximum income of mizuna was 203,306 yen at the third harvest in the TT plots. The maximum income of kabu shoots was 227,683 yen at the third harvest in the TT plots. The maximum income of spinach was 164,805 yen, but the size of the crop under the PVPs did not meet the shipping standard.
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for the seedlings—was higher than 1 and did not change substantially throughout the growing season (Fig. 9). Kabu adapted to low solar radiation conditions under the PVPs. We interpret this as indicating that spinach is not suitable for low temperature and low solar radiation conditions under the PVPs, because its FW and RSRUE were low compared with those of the other crops (Fig. 9). Contrastingly, since crops with high RSRUE experienced low delayed growth, mizuna and kabu are suitable for cultivation under PVPs in winter. However, mizuna should be harvested before bolting, which started at the time of the third harvest. For crops other than spinach, the RSRUE at the third harvest was >1, indicating that the ratio of FW per irradiance reached was greater under the PVPs than in the control plots. Although the FW of the TT plots with low solar radiation was small, the RSRUE of the TT plots was high, indicating that the light use efficiency was high. This result suggests that the suppression of radiative cooling by the PVPs reduced the low-temperature stress and increased the RSRUE.

The SPAD index, being highly correlated with chlorophyll content in the leaf, measures photosynthesis capacity (Kapotis et al., 2003; Netto et al., 2005; Kumagai et al., 2009). The maximum quantum yield of PSII, as indicated by Fv/Fm, being more readily used to understand the fundamental mechanisms of photosynthesis and the responses of plants to environmental change, is an indicator of environmental stresses, including drought, heat, chill, and salinity (Valladares and Pearcy, 1997; Allen and Ort, 2001; Salvucci and Crafts-Brandner, 2004; Jurmani et al., 2017). Accordingly, a reduced SPAD and Fv/Fm can reveal the degree of leaf senescence (Hilditch et al., 1986; Mattle et al., 1996; Crafts-Brandner et al., 1998; Hörtensteiner and Krüttler, 2011). SPAD and Fv/Fm of komatsuna and kabu in the TT and the CT were either higher than controls or did not differ from them significantly (Table 3), indicating an absence of senescence or stress from reduced solar radiation and low temperature under the PVPs. In the controls, displaying faster plant growth than that in the TT and the CT, Fv/Fm of komatsuna and kabu were lower. Notably, they appeared to be senescent. We conjecture that leaves in the control were senescent leaves, because the growth in the control occurred in the early stages. Since there was no significant difference in SPAD values of komatsuna, and the SPAD value of kabu controls was statistically lower than that of other treatments, kabu appeared to be more senescent than komatsuna. Although there were no significant differences among PVP conditions in SPAD and Fv/Fm in the mizuna that bolted earlier than other crops in this study, these values were lower than those of the other crops, suggesting that mizuna became senescent earlier than komatsuna and kabu.

We inferred that komatsuna was the most suitable crop for cultivation under PVPs because the conditions for maximum total income from crop and electricity sales were found during the third harvest of komatsuna in the TT plots (Fig. 5C, Table 4). We inferred from the total income that the TT conditions were suitable for komatsuna and kabu, while the CT conditions were suitable for mizuna. However, the growth of spinach under the PVPs was substantially delayed (Fig. 8B, C), thus, improvements such as an earlier sowing time or an extended cultivation period might be necessary. Furthermore, since the market price varies from day to day (Table 4), it is necessary to consider the cropping type in terms of the shipping time to maximize the total income.

CONCLUSION

In conclusions, we set up two agrivoltaic systems at the University of Miyazaki, and evaluated the effects on the growing environment of crops due to the shade created by the photovoltaic power generation facility. Although the growth rate of vegetables under agrivoltaic systems was slower than that under the controls, we obtained sufficient yields by prolonging the cultivation period. These results suggest that we will be able to produce both energy and food simultaneously using the same piece of land. Mizuna, however, must be harvested before losing its commercial value by bolting. Additionally, spinach grew slowly under the PVPs, and thus requires optimization of the growing period and the variety. RSRUE also becomes low when temperature and soil temperature are low (Vieira et al., 1998). Therefore, in order to raise the air and soil temperature for promotion of plant growth under PVPs, we recommend advancing the sowing date or using agricultural materials, such as mulch and tunnel. This study indicated that the harvesting time could be shifted depending on the presence or absence of solar panels, even if the sowing time was the same. These data suggest the possibility of distributing the labor force in terms of time, and it is expected to create a new crop system. The effect of PVPs on the suppression of radiative cooling and thermal barrier effect in summer and that of the crops suitable for this system need to be further investigated.

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