Original Paper

Environ. Control Biol., **60** (2), 117-127, 2022
DOI: 10.2525/ecb.60.117

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

Masaaki KIRIMURA[1], Shinichi TAKESHITA[1], Mitsuhiro MATSUO[1], Kazufumi ZUSHI[1],
Yoshinori GEJIMA[1], Chitose HONSHO[1], Akira NAGAOKA[2] and Kensuke NISHIOKA[2]

[1] *Faculty of Agriculture, University of Miyazaki, Miyazaki 889‒2192, Japan*
[2] *Research Center for Sustainable Energy & Environmental Engineering, University of Miyazaki, Miyazaki 889‒2192, Japan*

(Received March 26, 2021; Accepted September 26, 2021)

In a sustainable society, it is necessary to develop systems that produce enough 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

INTRODUCTION

Due to a growing human population and the concomitant increased demand for resources, the simultaneous production of sufficient food and energy without overly damaging the environment remains a serious issue that continues to limit sustainability (Tilman et al., 2009; Beddington, 2010; Harvey and Pilgrim, 2011; Steinbuks and Hertel, 2016). The need for new sources of renewable energy and the rising price of fossil fuels have created the anticipation of agricultural crops as a source of renewable energy in the future. With the rapid worldwide increase in photovoltaics to provide renewable energy, large areas of flat agricultural land are being converted to photovoltaic systems. Installation on flat land is optimal for harvesting solar radiation and has lower construction and maintenance costs than that in non-flat areas (Prados, 2010). Consequently, less land is now available for agriculture, raising the concern of decline in food production and rise in food prices in the future. In order to develop a sustainable system, it is therefore important to balance the production of renewable energy and food in utilizing the land (Nonhebel, 2005; Sacchelli et al., 2016).

Agrivoltaics—the installation of photovoltaic equipment onto farmland—are a novel approach for using a limited amount of land effectively. An agrivoltaic system integrating renewable energy sources into food production could provide extra income for growers (Dupraz et al., 2011). The shade created by photovoltaic panels above farmland, however, limits photon flux density at the ground level where the plants are grown, thereby reducing crop productivity. The Ministry of Agriculture, Forestry, and Fisheries of Japan therefore does not allow farmers to install agrivoltaic systems in agricultural fields unless productivity can be maintained above 80% of the yield generated without the system. The introduction of renewable energy sources into agricultural fields has consequently been limited. It is therefore necessary to examine crops that do not suffer much decrease in growth and yield due to shading.

Here, we examine strategies for converting solar radiation into both electric energy and food using agrivoltaics. Although some previous studies examined the effects of solar panels installed on the roofs of greenhouses (Tani et al., 2014), studies conducted in open agricultural fields are limited (Marrou et al., 2013a; 2013b). Particularly, the only crop used for those studies was lettuce. We therefore investigated the effect of shade generated by agrivoltaic systems on the yields of four vegetables (komatsuna, mizuna, kabu, and spinach) in an open field that, in winter, is otherwise not suitable for vegetable cultivation due to low temperatures and low levels of solar radiation, as well as examine the shading rate and identify the cropping systems suitable for agrivoltaics.

Corresponding author : Masaaki Kirimura,
e-mail : kirimura@cc.miyazaki-u.ac.jp

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°83′ 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.

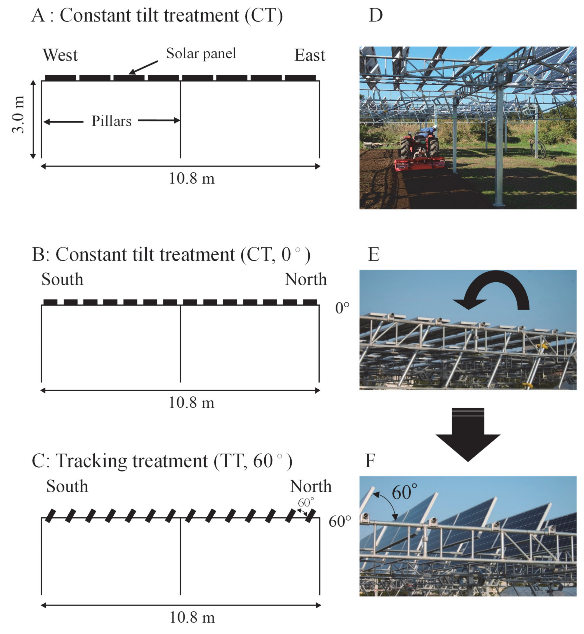

Fig. 1 Side view of the models of the tested agrivoltaic system (A–C). The situation of the tilling works using a tractor under the system (D). The photovoltaics panel was an angled variable type (B, C, E, F). Constant tilt treatment at 0° (B, E) and tracking treatment at 60° in December and January (C, F).

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 P_2O_5 ha^{-1}, and 140 kg K_2O 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).

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)^z	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)		

^{z} Numbers in parentheses indicate days after sowing.

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 harvests 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-502Plus, KONICA MINOLTA JAPAN, Inc., Tokyo, Japan) on February 27, 2015.

We measured maximum photochemical quantum yields of photosystem II (PSII) (Fv/Fm $= \phi_{P0}$) 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:

$$RSRUE = (FW_{TT\ or\ CT}/SR_{TT\ or\ CT})/(FW_{control}/SR_{control})$$

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℃ and lowest in the TT plots at 7.8℃. 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℃ and 3.5℃, 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℃, followed by that in the TT plots at 3.6℃ and CT plots at 3.7℃ (Fig. 3C). The mean diurnal air temperature range was largest in the control plots at 10.2℃ and lowest in the TT plots at 9.0℃ (Fig. 3D). Soil temperature was reduced in the shade. In particular, the minimum soil temperature in the TT plots was lower by approximately 2℃ than that of both the CT and control plots (Fig. 4).

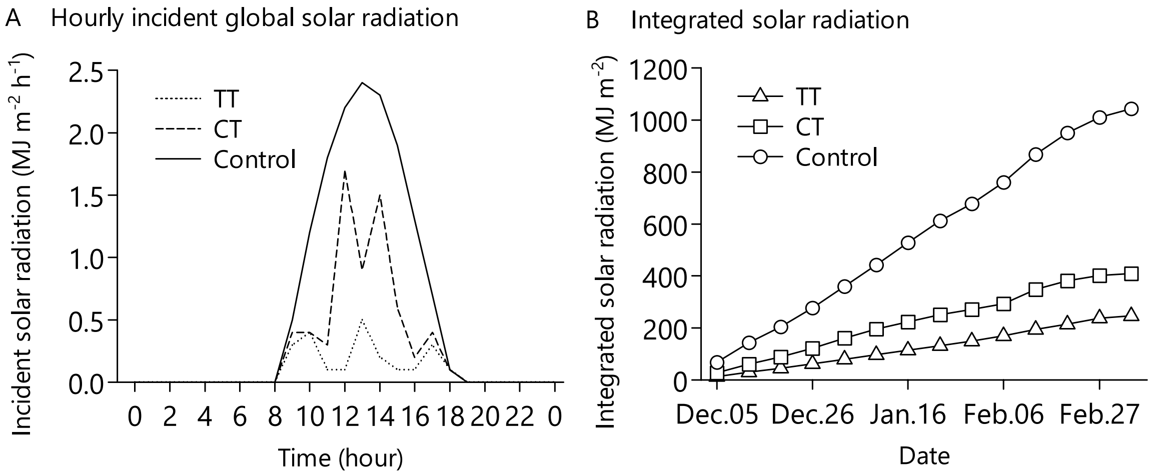

Fig. 2 Hourly incident global solar radiation in the TT treatment, in the CT treatment, and the control on a typical sunny day. We conducted the measurement on January 6, 2015 (A). Integrated solar radiation in the TT treatment, the CT treatment, and the control (B).

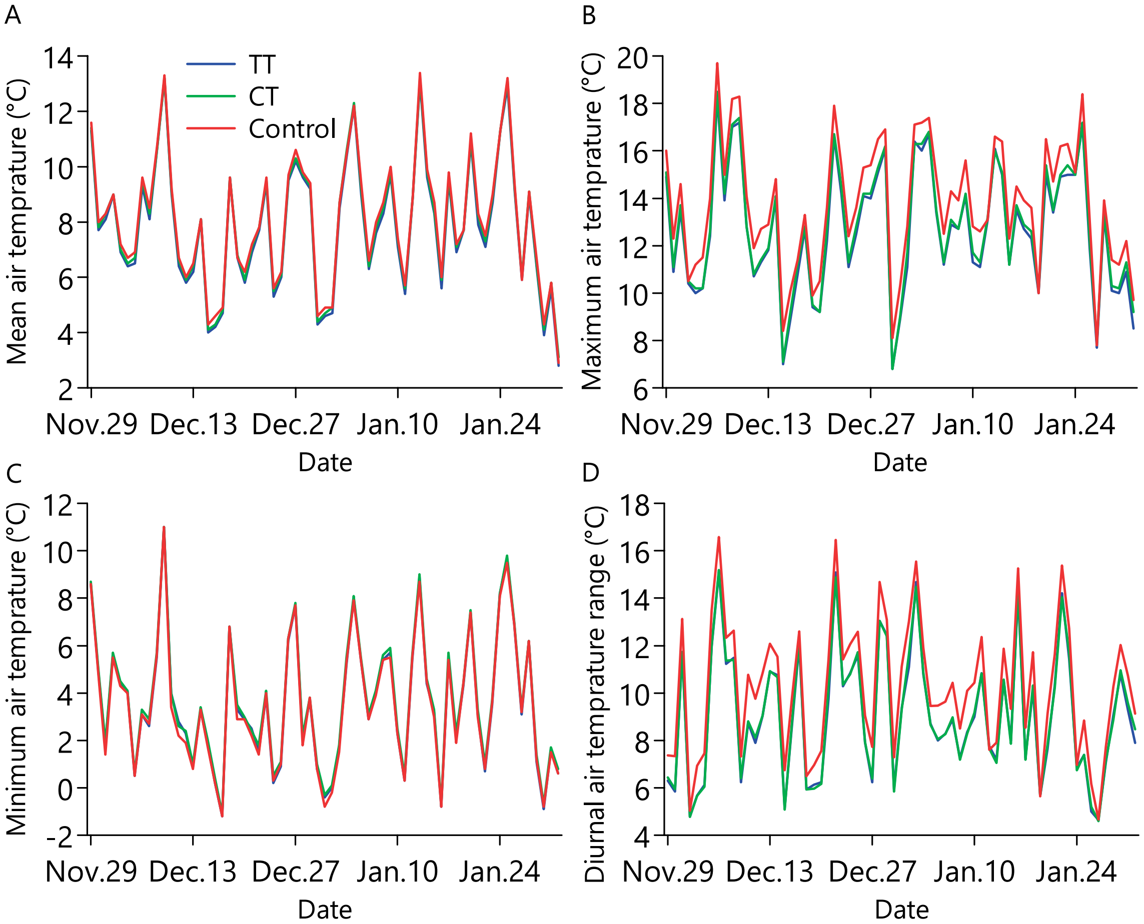

Fig. 3 Mean daily air temperature (A), daily maximum air temperature (B), daily minimum air temperature (C), and diurnal air temperature range (D) in the TT treatment, the CT treatment, and the control.

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

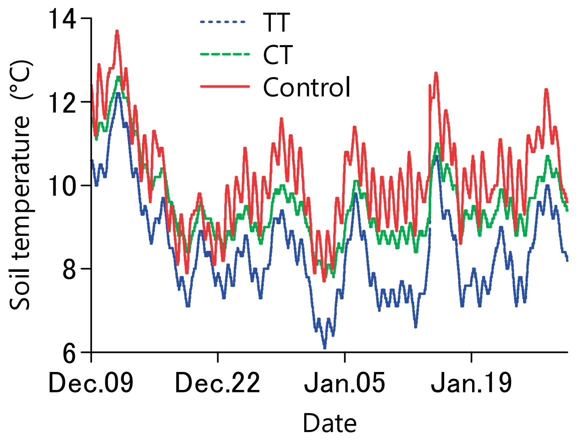

Fig. 4 Soil temperature in the TT treatment, the CT treatment, and the control.

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,

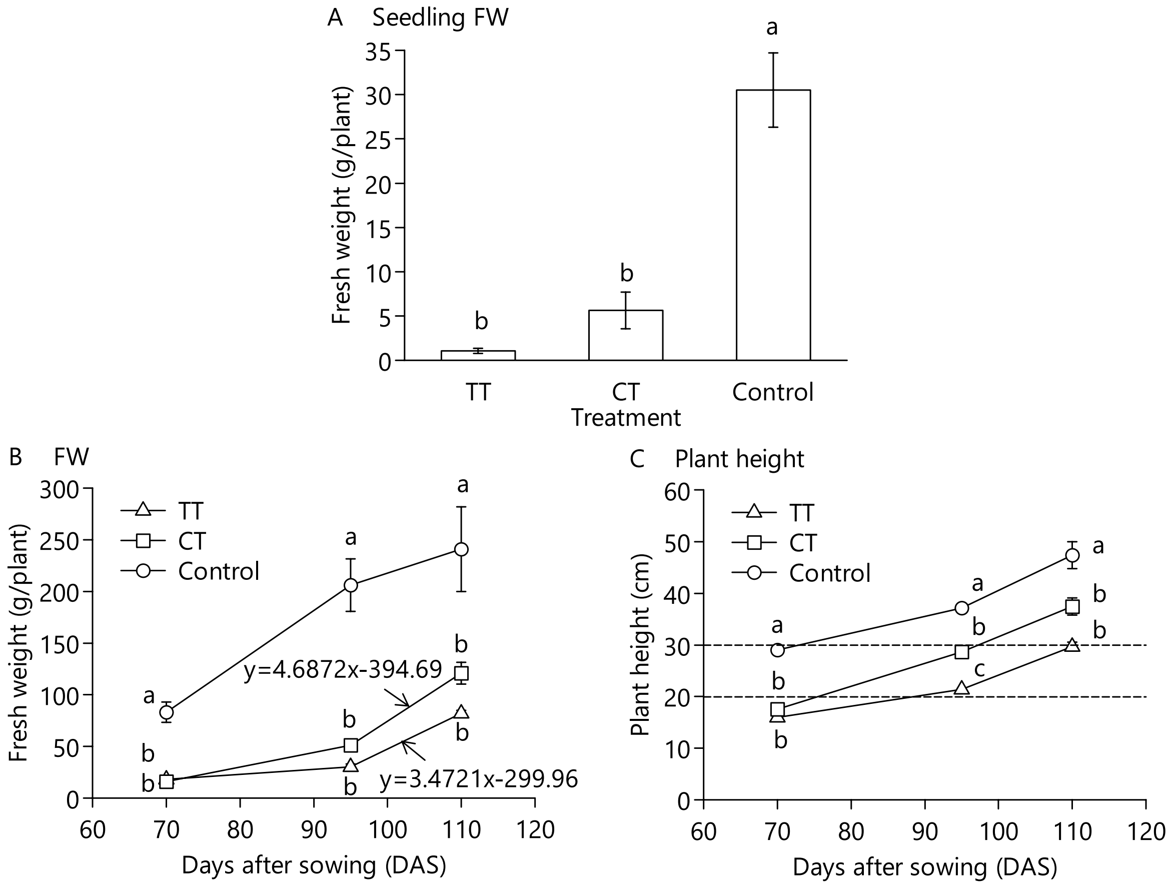

Fig. 5 Effect of shading treatments by photovoltaic panels on the seedling FW (A) of komatsuna at 46 days after sowing (DAS) (mean±SE, $n = 6$). The fresh weight (B) and plant height (C) of komatsuna at three different harvest times (mean±SE, $n = 5$–10). We used regression equations to determine when the FW of the TT or CT plots reach the level of the control plots. The two dashed lines indicate the maximum and minimum plant height requirements for the shipment standard for the Japanese vegetable market. Different letters within the same harvest time indicate significant differences by Tukey–Kramer test at $P < 0.05$.

Table 3 Effects of shading treatments by photovoltaic panels on SPAD value and Fv/Fm of leaves at 108 DAS (mean±SE, $n = 24$).

Measurement	Treatment	Komatsuna		Mizuna		Kabu	
	TT	54.1±1.1	a^z	28.5±1.0	A	43.0±1.6	a
SPAD value	CT	51.8±1.4	a	27.8±0.7	A	39.7±0.9	ab
	Control	55.3±1.6	a	28.8±0.7	A	36.5±0.9	b
	TT	0.821±0.005	a	0.787±0.005	A	0.820±0.004	a
Fv/Fm	CT	0.805±0.011	ab	0.777±0.009	A	0.822±0.008	a
	Control	0.785±0.008	b	0.768±0.019	A	0.783±0.010	b

^{z} Different letters within each crop indicate significant differences by Tukey–Kramer test at $P < 0.05$.

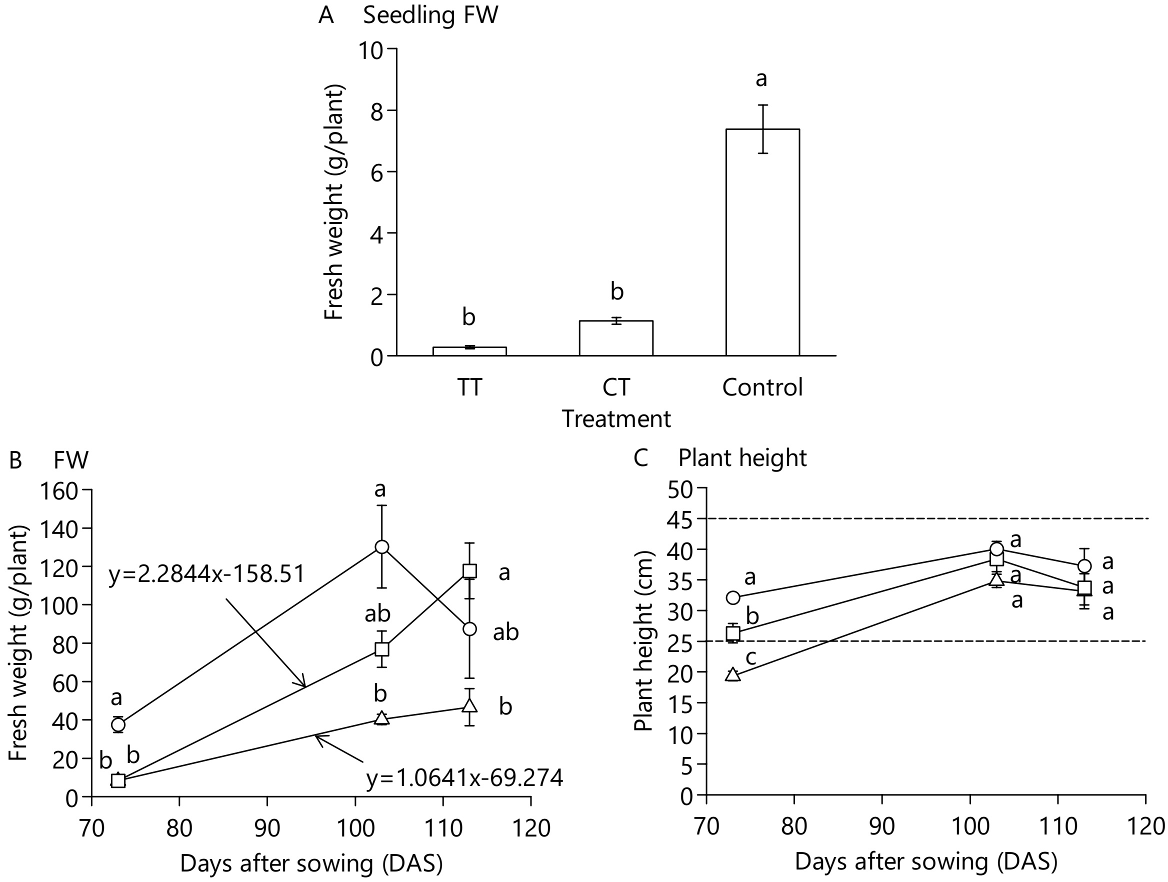

Fig. 6 Effect of shading treatments by photovoltaic panels on the seedling FW (A) of mizuna at 53 days after sowing (DAS) (mean±SE, $n = 6$). The fresh weight (B) and plant height (C) of mizuna at three different harvest times (mean±SE, $n = 5$–10). We used regression equations to determine when the FW of the TT or CT plots reach the level of the control plots. The two dashed lines indicate the maximum and minimum plant height requirements for the shipment standard for the Japanese vegetable market. Different letters within the same harvest time indicate significant differences by Tukey–Kramer test at $P < 0.05$.

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 FW of 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

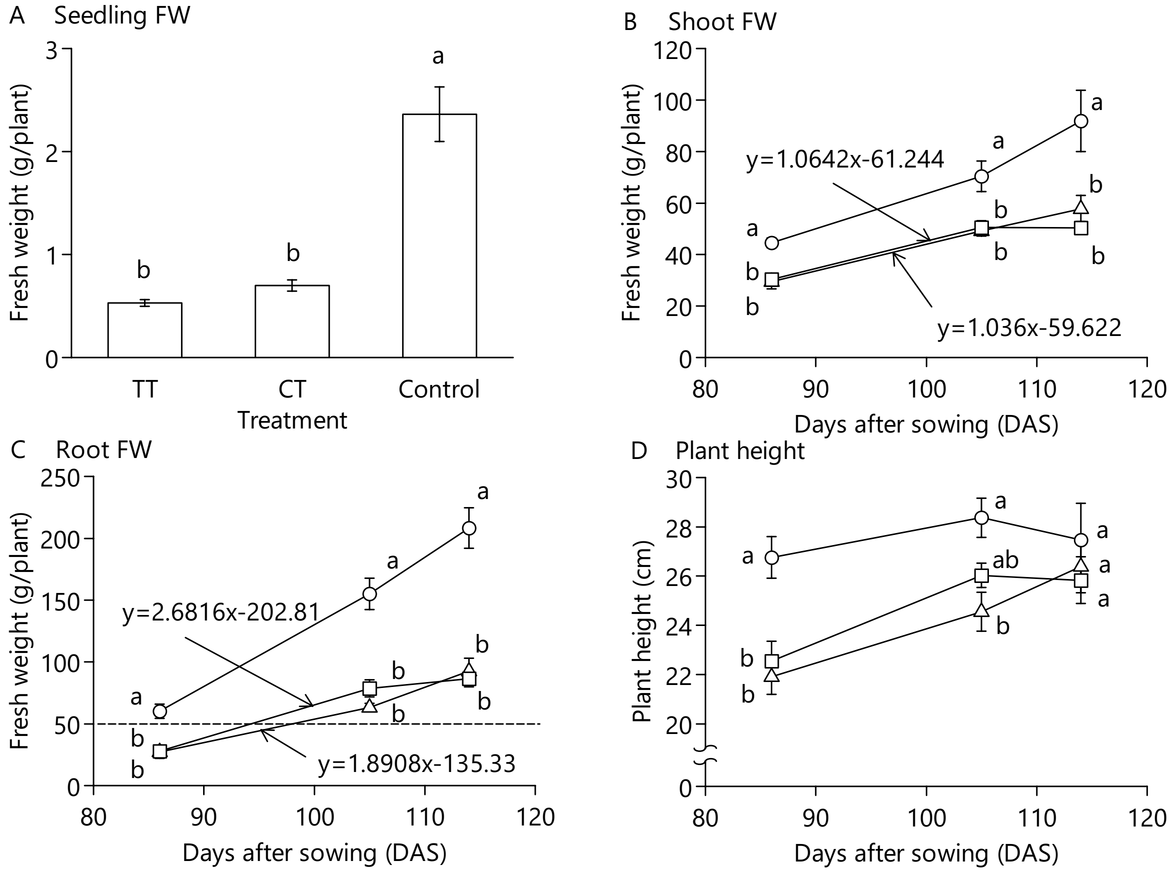

Fig. 7 Effect of shading treatments by photovoltaic panels on the seedling FW (A) of kabu shoot at 53 days after sowing (DAS) (mean±SE, $n = 6$). The fresh weight of kabu shoots (B), kabu roots (C) and plant height of kabu shoots (D) at three different harvest times (mean±SE, $n = 5$–10). We used regression equations to determine when the FW of the TT or CT plots reach the level of the control plots. The horizontal dashed line indicates when the fresh weight of kabu roots reached 5 cm in diameter in the control group, meeting the shipment standard for the Japanese vegetable market. Different letters within the same harvest time indicate significant differences by Tukey–Kramer test at $P < 0.05$.

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 controls 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 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

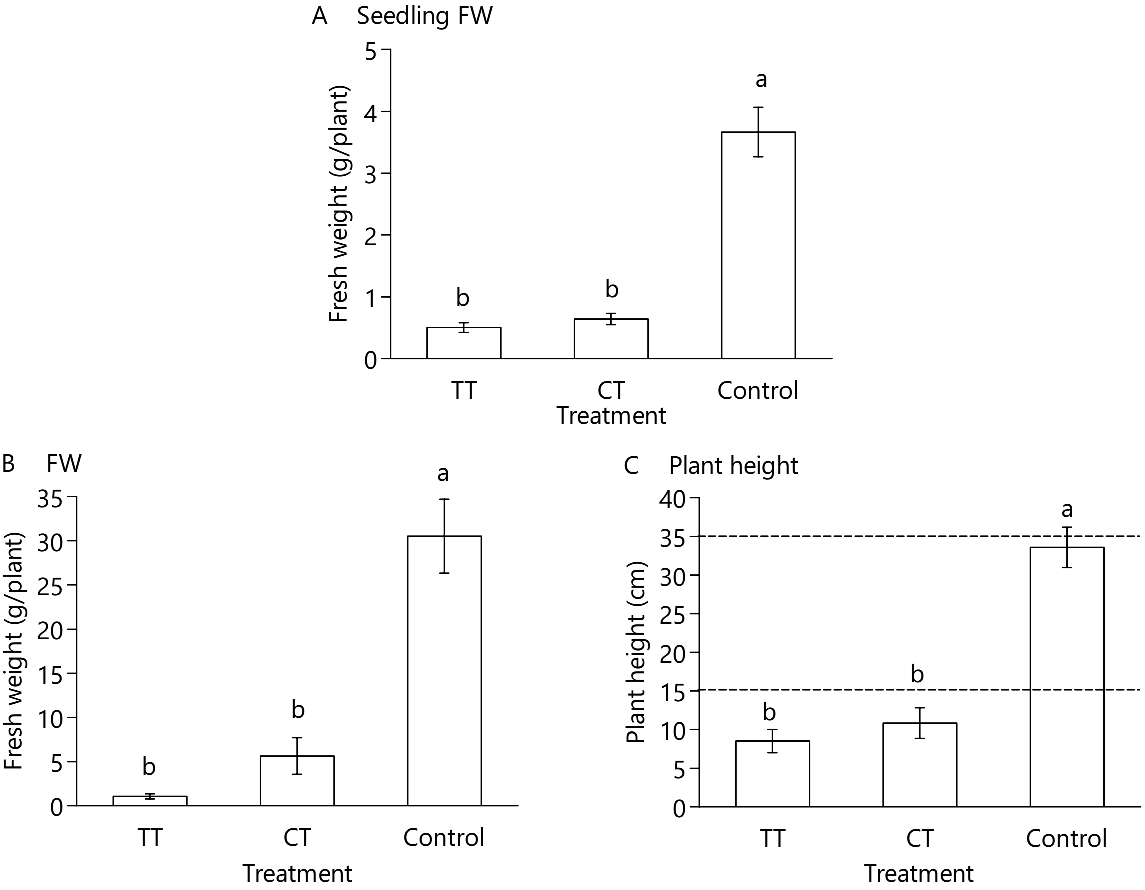

Fig. 8 Effect of shading treatments by photovoltaic panels on the seedling FW (A) of spinach (mean±SE, $n = 6$). The fresh weight (B) and plant height (C) of spinach at three different harvest times (mean±SE, $n = 5$–10). The two dashed lines indicate the maximum and minimum plant height requirements for the shipment standard for the Japanese vegetable market. Different letters indicate significant differences by Tukey–Kramer test at $P < 0.05$.

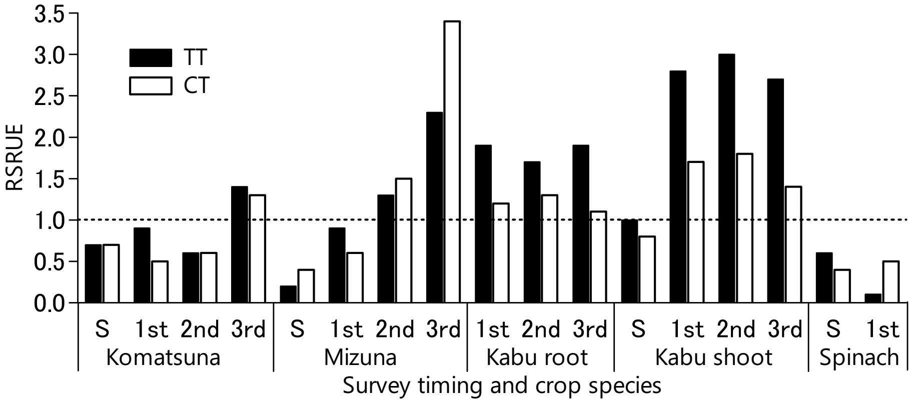

Fig. 9 Relative solar radiation use efficiency (RSRUE) values of komatsuna, mizuna, kabu root, kabu shoot, and spinach at seedling (S), first (1st), second (2nd), and third (3rd) harvests cultivated in TT (black bars) and CT (white bars). The horizontal dashed line indicates the RSRUE (1.0) of the control plots, which serves as the standard for comparison.

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

Table 4 Effect of shading treatments by photovoltaic panels on crop income, power generation income, and total income.

Crop	Number of harvests	Market price (yen/kg)	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	79,190	153,127	117,152	202,471
	2nd	431	66,783	113,047	461,230	132,996	98,857	199,780	211,903	461,230
	3rd	329	139,806	206,206	411,041	167,851	131,987	307,658	338,193	411,041
Mizuna	1st	443	6,436	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	203,306	48,353
Kabu shoot	1st	437	22,257	22,864	33,690	134,130	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	138,436	205,108	165,326	49,057
Kabu root	1st	126	5,940	6,053	13,085	134,130	100,041	140,070	106,095	13,085
	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	138,436	196,855	159,541	50,747
Kabu shoot and root	1st							162,327	128,959	46,775
	2nd							205,409	174,800	83,126
	3rd							227,683	186,430	99,804
Spinach	1st	443	2,457	12,975	70,080	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/tokei/kouhyou/seika_orosi/ (Accessed 11 March 2021).

and the CT to second harvest was lower than that of the control (1.0) (Fig. 9). In the third harvest, since the FW of komatsuna in the TT and the CT increased greatly, the RSRUE of komatsuna in the TT and the CT was higher than that of the controls. The RSRUE of mizuna was similar to that of komatsuna. Together with the lower solar radiation intensity under PVPs, the lower RSRUE would explain the lower early relative growth rate observed in komatsuna and mizuna. The RSRUE of kabu roots and shoots was >1 except for the seedling of kabu shoots, whereas that of spinach was <1 in seedling and first harvest, where first harvest was lower than other crops.

Economic assessment

The total income of komatsuna under the PVPs was lower than that of the control (Table 4). 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 income of mizuna was 203,306 yen at the third harvest in the CT plots, and the maximum total income of kabu (shoot and root) 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.

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 for the seedlings—was higher than 1.0 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; Jumrani et al., 2017). Accordingly, a reduced SPAD and Fv/Fm can reveal the degree of leaf senescence (Hilditch et al., 1986; Matile et al., 1996; Crafts-Brandner et al., 1998; Hörtensteiner and Kräutler, 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.

ACKNOWLEDGEMENTS

This work was partially supported by a grant from the Strategic Research Budget of the University of Miyazaki and JSPS KAKENHI Grant Number JP12345678. The authors are grateful to Looop Inc. for offering research materials. The authors have no competing interests to declare.

REFERENCES

Allen, D. J., Ort, D. R. 2001. Impacts of chilling temperatures on photosynthesis in warm-climate plants. Trends Plant Sci. **6**: 36–42.

Andrade, F. H., Uhart, S. A., Cirilo, A. 1993. Temperature affects radiation use efficiency in maize. Field Crops Res. **32**: 17–25.

Beddington, J. 2010. Food security: contributions from science to a new and greener revolution. Philos. Trans. R. Soc. B Biol. Sci. **365**: 61–71.

Crafts-Brandner, S. J., Hölzer, R., Feller, U. 1998. Influence of nitrogen deficiency on senescence and the amounts of RNA and proteins in wheat leaves. Physiol. Plant. **102**: 192–200.

Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., Ferard, Y. 2011. Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. Renew. Energ. **36**: 2725–2732.

Fallovo, C., Colla, G., Schreiner, M., Krumbein, A., Schwarz, D. 2009. Effect of nitrogen form and radiation on growth and mineral concentration of two *Brassica* species. Sci. Hortic. **123**: 170–177.

Francescangeli, N., Sangiacomo, M. A., Martí, H. 2006. Effects of plant density in broccoli on yield and radiation use efficiency. Sci. Hortic. **110**: 135–143.

Harvey, M., Pilgrim, S. 2011. The new competition for land: food, energy, and climate change. Food Policy **36**: S40–S51.

Hilditch, P., Thomas, H., Rogers, L. 1986. Leaf senescence in a non-yellowing mutant of *Festuca pratensis*: photosynthesis and photosynthetic electron transport. Planta **167**: 146–151.

Hörtensteiner, S., Kräutler, B. 2011. Chlorophyll breakdown in higher plants. Biochim. Biophys. Acta Bioenerg. **1807**: 977–988.

Jumrani, K., Bhatia, V. S., Pandey, G. P. 2017. Impact of elevated temperatures on specific leaf weight, stomatal density, photosynthesis and chlorophyll fluorescence in soybean. Photosynth. Res. **131**: 333–350.

Kadowaki, M., Yano, A., Ishizu, F., Tanaka, T., Noda, S. 2012. Effects of greenhouse photovoltaic array shading on Welsh onion growth. Biosyst. Eng. **111**: 290–297.

Kapotis, G., Zervoudakis, G., Veltsistas, T., Salahas, G. 2003. Comparison of chlorophyll meter readings with leaf chlorophyll concentration in amaranthus vlitus: correlation with physiological processes. Russ. J. Plant Physiol. **50**: 395–397.

Kawamura, K., Cho, M., Takeda, H. 2005. The applicability of a color acetate film for estimating photosynthetic photon flux density in a forest understory. J. For. Res. **10**: 247–249.

Kumagai, E., Araki, T., Kubota, F. 2009. Correlation of chlorophyll meter readings with gas exchange and chlorophyll fluorescence in flag leaves of rice (*Oryza sativa* L.) plants. Plant Prod. Sci. **12**: 50–53.

Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., Wery, J. 2013a. Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? Agric. For. Meteorol. **177**: 117–132.

Marrou, H., Wery, J., Dufour, L., Dupraz, C. 2013b. Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. Eur. J. Agron. **44**: 54–66.

Matile, P., Hörtensteiner, S., Thomas, H., Kräutler, B. 1996. Chlorophyll breakdown in senescent leaves. Plant Physiol. **112**: 1403–1409.

New Energy and Industrial Technology Development Organization. 2012. The database of solar radiation "MONSOLA-11". https://www.nedo.go.jp/library/nissharyou.html (Accessed 11 March 2021).

Netto, A. T., Campostrini, E., Oliveira, J. G. D., Bressan-Smith, R. E. 2005. Photosynthetic pigments, nitrogen, chlorophyll a fluorescence and SPAD-502 readings in coffee leaves. Sci. Hortic. **104**: 199–209.

Ministry of Agriculture, Forestry and Fisheries. 2015. Wholesale market survey of fruits and vegetables (daily survey). https://www.maff.go.jp/j/tokei/kouhyou/seika_orosi/ (Accessed 11 March 2021).

Nonhebel, S. 2005. Renewable energy and food supply: will there be enough land? Renew. Sust. Energ. Rev. **9**: 191–201.

Prados, M. J. 2010. Renewable energy policy and landscape management in Andalusia, Spain: the facts. Energy Policy **38**: 6900–6909.

Rizzalli, R. H., Villalobos, F. J., Orgaz, F. 2002. Radiation interception, radiation-use efficiency and dry matter partitioning in garlic (*Allium sativum* L.). Eur. J. Agron. **18**: 33–43.

Sacchelli, S., Garegnani, G., Geri, F., Grilli, G., Paletto, A., Zambelli, P., Ciolli, M., Vettorato, D. 2016. Trade-off between photovoltaic systems installation and agricultural practices on arable lands: an environmental and socio-economic impact analysis for Italy. Land Use Policy **56**: 90–99.

Salvucci, M. E., Crafts-Brandner, S. J. 2004. Relationship between the heat tolerance of photosynthesis and the thermal stability of rubisco activase in plants from contrasting thermal environments. Plant Physiol. **134**: 1460–1470.

Stagnari, F., Galieni, A., Pisante, M. 2015. Shading and nitrogen management affect quality, safety and yield of greenhouse-grown leaf lettuce. Sci. Hortic. **192**: 70–79.

Steinbuks, J., Hertel, T. W. 2016. Confronting the food–energy–environment trilemma: global land use in the long run. Environ. Resour. Econ. **63**: 545–570.

Tani, A., Shiina, S., Nakashima, K., Hayashi, M. 2014. Improvement in lettuce growth by light diffusion under solar panels. J. Agric. Meteorol. **70**: 139–149.

Tei, F., Scaife, A., Aikman, D. P. 1996. Growth of lettuce, onion, and red beet. 1. Growth analysis, light interception, and radiation use efficiency. Ann. Bot. **78**: 633–643.

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R. 2009. Beneficial biofuels—the food, energy, and environment trilemma. Science **325**: 270–271.

Valladares, F., Pearcy, R. W. 1997. Interactions between water stress, sun-shade acclimation, heat tolerance and photoinhibition in the sclerophyll *Heteromeles arbutifolia*. Plant Cell Environ. **20**: 25–36.

Vieira, I. S., Vasconcelos, E. P., Monteiro, A. A. 1998. Nitrate accumulation, yield and leaf quality of turnip greens in response to nitrogen fertilisation. Nutr. Cycl. Agroecosys. **51**: 249–258.