HortScience 60(6):841–851. 2025. https://doi.org/10.21273/HORTSCI18537-25

Impact of Agrivoltaic Shade on Beet Curly Top Virus and Yield in Chile Pepper (*Capsicum annuum*)

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Keywords. BCTV, light intensity, photovoltaic, solar panels

Abstract. ***Curtovirus*** **spp., a group of widely distributed geminiviruses, are among the most significant plant pathogens in the United States. Beet curly top virus (BCTV), vectored by the beet leafhopper [*****Circulifer*** **(*****Neoaliturus*****)** ***tenellus*** **Baker], causes severe economic losses in crops such as tomatoes, peppers, dry beans, sugar beets, melons, and leafy greens, particularly in the western United States. In New Mexico, chile (*****Capsicum annuum*****) is vulnerable, with infected plants exhibiting symptoms such as stunting, chlorotic and curled leaves, misshapen fruits, reduced yields, and plant death. Yield losses can reach up to 50% in some years. Current management strategies, including pesticide applications, provide limited protection, leaving growers with substantial losses. Research indicates beet leafhoppers prefer full sun and avoid shaded areas, suggesting potential for innovative pest management strategies. Agrivoltaic systems (AVSs), which combine photovoltaic (PV) installations with agriculture, increase field shade and could potentially deter crop pests. However, the effect of AVS on pest management and chile crop yields remains underexplored. This study evaluated the impact of AVS shade on chile yield and plant growth, beet leafhopper abundance, and BCTV incidence. In 2023 and 2024, 'NuMex Odyssey', a New Mexico type chile cultivar, was grown in PV module–shaded and full sun replications at New Mexico State University's Leyendecker Plant Science Research Center. PV modules provided shade to plants during the morning hours (0630 to 1330 HR), resulting in an 11% reduction in mean light intensity compared with the full sun replications. Full sun replications had more marketable green yield, while PV shaded replications exhibited significantly lower BCTV-affected fruit in 2024 and beet leafhopper abundance in both 2023 and 2024. These findings suggest that shading can reduce beet leafhopper abundance and BCTV incidence, offering potential benefits for chile cultivation.**

Agrivoltaics (AVS) is an innovative approach that integrates photovoltaic (PV) panel energy generation with agricultural production on the same land. Initially proposed in the early 1980s by Goetzberger and Zastrow (1982), this dual-use concept has attracted considerable interest from researchers in the past decade. Agrivoltaics encompasses a range of applications, including the colocation of grazing animals and crop cultivation (Macknick et al. 2022). Research on agrivoltaic crop production has been conducted worldwide focusing on various aspects such as PV system design, crop selection, modeling of light distribution over time and space, crop growth and yields, and environmental conditions within the system (Trommsdorff et al. 2022). There have been many studies evaluating how large-scale PV arrays and agrivoltaic systems affect pollinator insect populations (Graham et al. 2021a, 2021b; Grodsky et al. 2021; Walston et al. 2023). One underexplored area of agrivoltaic crop production research is the study of insect pest populations. An insect is considered a pest if it causes damage to the harvested product at levels deemed unacceptable by the producer (Dent and Binks 2020). Understanding pest behavior is essential for the success of crop production systems. Worldwide insect pests can cause 40% crop loss during any given year (Food and Agriculture Organization 2022a). Typically, producers use insecticides to control pests, and the worldwide application rate of pesticides per area of cropland was 1.8 $kg \cdot ha^{-1}$ (Food and Agriculture Organization 2022b).

Integrated pest management (IPM), introduced 25 years ago (Kogan 1998), is a sustainable, science-based decision-making approach designed to control pests effectively. It integrates biological, cultural, physical, and chemical tools to identify, manage, and mitigate risks posed by pests while minimizing economic, health, and environmental impacts (US Department of Agriculture 2018). IPM management tools for pest insects include techniques, methodologies, and processes that producers can implement to minimize economic losses and reduce overall insecticide use.

One of the most prevalent chile (*Capsicum annuum*) diseases is beet curly top virus (BCTV). Beet leafhoppers [*Circulifer* (*Neoaliturus*) *tenellus* Baker] transmit BCTV and are endemic to arid to semiarid areas in the western and southwestern United States (Creamer 2003). BCTV was first reported in 1927 in New Mexico (Crawford 1927). Beet leafhoppers have various hosts and cause damage to crops including peppers, tomatoes, and leafy greens (Creamer 2003). Currently, there is no fully effective method for controlling beet leafhoppers (Creamer et al. 2004). While producers often use insecticides as a control measure, these treatments are limited in their effectiveness. Various IPM strategies have been investigated to better understand how to control beet leafhoppers (Creamer et al. 2005). Understanding pest behavior is a critical component of IPM strategies, and previous research has shown that beet leafhoppers exhibit a preference for feeding in full sun (Oldfield et al. 1991).

In New Mexico, chile pepper yield losses from curly top vary from 0.5% to 50% depending on the year (Lehnhoff and Creamer 2020). Once infected with BCTV, chile plants can display many symptoms including stunted growth, chlorotic/curling leaves, and abnormal fruit production. BCTV-infected plants display symptoms differently depending on the stage of growth in which they were infected. Early infection of BCTV can halt fruit production, and infection in a later stage of growth can cause abnormal fruiting (Creamer et al. 2004).

Chile is an important crop used as a vegetable, spice, and food colorant. It has been cultivated in New Mexico for over four centuries (Bosland and Walker 2014). Chile is an integral part of New Mexican farming, cuisine and culture. In 2023, New Mexico produced over 46,000 tons of chile, valued at more than 41 million dollars (US Department of Agriculture, National Agricultural Statistics Service 2023). Green chile has a high production value, yet its production in New Mexico has been steadily declining (US Department of Agriculture, National Agricultural Statistics Service 2023). Meanwhile, imports and consumer demand continue to rise (Lillywhite and Robinson 2023; Wechsler 2023). The potential loss of green chile production represents more than an agricultural challenge—it threatens a deeply rooted cultural tradition and exacerbates food insecurity throughout the United States. This decline has been linked to several factors, including rising temperatures, water scarcity, increased disease pressures, and labor shortages.

In the pursuit of innovative IPM tools to support green chile producers, AVSs have emerged as a promising solution. The partial shading provided by PV panels in production fields may serve a dual purpose: deterring beet leafhoppers while simultaneously enhancing overall farm income through renewable energy generation. The objective of this study was to evaluate the impact of AVS shade on chile yields, beet leafhopper abundance, and the incidence rate of BCTV.

Materials and Methods

This study was conducted in 2023 and 2024 at the New Mexico State University, Leyendecker Plant Science Research Center (lat. 32.20°N, long. 106.74°W). The study area soil is Belen clay loam, a well-drained soil with the taxonomic class clayey over loamy, smectitic over mixed, superactive, calcareous, thermic Vertic Torrifluvents (National Resources Conservation Services 2024).

Study site. For this study, an experimental PV array was installed in an existing production field. Four single-pile, fixed tilt racking systems were custom built (RC Rab Corporation, Albuquerque, NM, USA) and mounted with four decommissioned PV panels (Trinasolar TSM-240PA05; New Mexico State University, Solar Experiment Station, Las Cruces, NM, USA). The PV module installation faced limitations due to field's orientation and the goal of using low-impact procedures to minimize soil disturbance. The field is oriented at 224.67° southwest, and the PV modules were aligned accordingly and installed outside the last row (Fig. 1) with 12.2 m spacing between each pile. To minimize soil compaction in the production area, the modules were installed along the edge of the field rather than within the field itself. Each module was pile-driven into the ground without using a concrete foundation.

The installed PV modules could be manually tilted to various angles (Fig. 2). When farm machines were in the field, all modules were in the stow position (Fig. 3). During the experimental period, all modules were set to the experimental position with an 11° tilt, facing east.

Experimental design. In both years, the plots were arranged in a randomized complete block design, with PV module shade and full sun as the treatments. There was one full sun and four PV module replications 2023. In 2023, there was only one complete sun replication because several plants died and had to be replanted. In 2024, there were four PV module and full sun replications (Fig. 4).

Each replication consisted of three rows: row 1 closest to the pile, row 2 in the middle; and row 3 furthest from the pile. Rows 1 and 3 were border rows, while the innermost part of row 2 was designated the sample row. The sample area was 3.7 m long by 1 m wide (3.7 m^2; Fig. 5). The sample area was further divided into four transects to accurately represent the environmental variation across the area. Each transect was 0.9 m long by 1 m wide (0.9 m^2).

Plant material and field management. 'NuMex Odyssey', a green chile pod-type cultivar developed for mechanical harvest (Walker et al. 2021), was selected for this study. In 2023 and 2024, 'NuMex Odyssey' was seeded in the greenhouse at the Fabian Garcia Research Center in Las Cruces, NM, USA, on 10 Mar 2023 and 11 Mar 2024, respectively. The seeds were planted into a commercial peatmoss−vermiculite soil mixture (RediEarth Plug and Seedling Mix; Sun Gro Horticulture, Bellevue, WA, USA) in polyethylene trays (TOD812; T.O. Plastics, Clearwater, MN, USA). Transplants were hardened off under a shade house starting on 20 Apr 2023 and 19 Apr 2024. The seedlings were transplanted into the Plant Science Research Center field on 10 May 2023 and 1 May 2024 in single rows with 30.5 cm between-plant spacing with a single line of subsurface drip irrigation tubing [12 inches emitter spacing, 0.23 gal/100 ft per hour at 10.0 psi (Netafim, Fresno, CA, USA)]. The proximity of row 1 to the PV modules prevented the mechanical burial of subsurface drip irrigation, so this border row used surface drip irrigation. Composite soil tests were completed on 20 Mar 2023 and 26 Mar 2024 (Ward Laboratories, Kearney, NE, USA).

Soil tests indicated that preplant fertilizer was unnecessary; however, fertilizer was applied through the drip irrigation system throughout each season to meet the nutrient demands of the chile (Bosland and Walker 2014). For both years N-pHuric with 28N−0P−0K+9(S) (Helena Chemical Company, Albuquerque, NM, USA) was applied at 156 lb/acre (25.4 kg/4046.86 m^2) Hand cultivation was performed twice at the beginning of each season, while hand weeding was completed weekly throughout the season.

Fig. 1. Site map shows field alignment along photovoltaic panel modules at Leyendecker Plant Science Research Center, Las Cruces, NM, USA.

Measurements

Light intensity and ambient air temperature. Light intensity (lux) and ambient air temperature (°C) measurements were taken every hour using in situ self-logging sensors (Hobo Pendant MX2202; Onset, Bourne, MA, USA) mounted on fence posts 1 m above the ground. All replications had four light/temperature sensors; each sensor was positioned in the center of each of the transects within the sample area (Fig. 6).

Beet leafhopper abundance. Beet leafhopper population numbers were collected using yellow sticky trap cards measuring 10 cm wide and 25 cm long (250 cm^2) with adhesive on both sides (Pest Trap; Hummert International, Earth City, MO, USA). Sticky cards were placed 61 cm above the ground attached to a wooden post (Creamer 2003). There were two sticky trap locations, 61 cm from the centers of row 3 and row 1, respectively (Fig. 5). Sticky cards were replaced every 2 weeks throughout the season until harvest. Sticky traps were examined, and beet leafhoppers were counted.

Photosynthesis. Leaf-level net carbon dioxide assimilation (A_{net}) was measured at

Fig. 2. Connecting hinge of steel racking system that allows manual adjustment of tilt installed photovoltaic modules.

Received for publication 17 Feb 2025. Accepted for publication 13 Mar 2025.
Published online 6 May 2025.
This project was supported by the New Mexico Department of Agriculture Specialty Crop Block Program.
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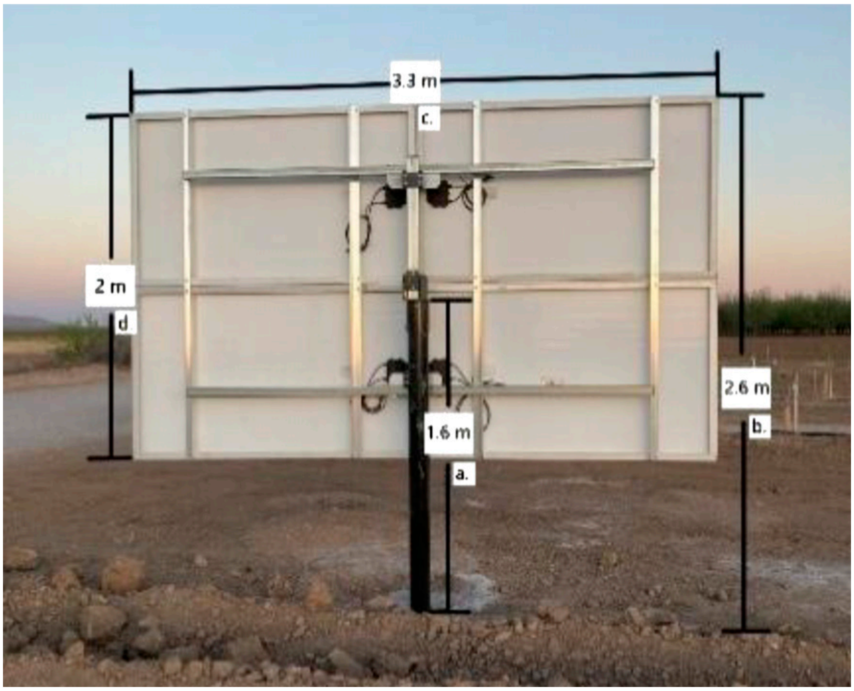

Fig. 3. Fixed tilt steel racking system supporting four decommissioned photovoltaic (PV) panels in the stow position. Dimensions of PV module system in stow position are given. (**a**) Pile height from ground to top of the connecting hinge. (**b**) Height from ground to highest point of PV module. (**c**) Widest point of PV module. (**d**) Length of mounted PV panels.

peak vegetative stage using a portable photosynthesis system (LI-6800; LI-COR Biosciences, Lincoln, NE, USA). The same three randomly selected plants were measured from each replication six times, from 1000 to 1300 HRon 10, 12, and 13 Jul in 2023 and 15, 16, and 17 Jul 2024 (Fig. 7). All measurements were made on recently mature, fully expanded, upper canopy leaves. The LI-6800 was equipped with a 3-cm × 3-cm cuvette head and a red−blue LED light source. During all measurements, the following settings were maintained: a constant flow rate of 500 μmol·s^{-1}, relative humidity at 60%, carbon dioxide concentration at 400 μmol·s^{-1}, a fan speed of 1000 with the mixing fan activated, light intensity at 1500 μmol·s^{-1}, and a stomatal ratio of 0.5.

Plant growth measurements. Plant architecture measurements were taken every 3 weeks starting at the initial transplantation. Measurements were taken on all 12 plants from the sample area. Measurements included plant height (cm) and basal diameter (mm). Plant height was taken from the ground level at the base of the plant to the highest meristem. Basal stem diameter was taken at the base of the stem directly above ground level using a digital caliper (Absolute Digimatic Caliper; Mitutoyo, Aurora, IL, USA). Due to differences in season length, plant architecture measurements were collected four times in 2023 and five times in 2024. This variation in sampling frequency was addressed in the analysis by evaluating each year separately.

Harvested fruit. The fresh weight of chile was taken at harvest on 25 Aug 2023 and 29 Aug 2024. All plants were hand harvested from the 3.7-m^2 sample area. Harvested fruit were sorted into several categories; 1) marketable green, intact whole unblemished fruit that is at a horticulturally mature green stage and is suitable for market; 2) blossom end rot (BER) affected fruit with BER symptoms, blackened apex (Goldberg 1995); 3) red fruit, intact whole unblemished fruit at ripe red stage; 4) diseased fruit, whole unmarketable fruit that has blemishes and indication of disease; 5) immature fruit, green fruit with malleable pericarps; and 6) BCTV-affected fruit, abnormal block-shaped small fruit (Fig. 8).

Statistical analysis. The experiment did not follow any standard design, and for that reason, during the data analysis, some correlations structures were included to account for the lack of randomization. The PV module study site was established in 2023 and used again in 2024. In the first year, the full sun treatment was replicated once, while the PV module treatment had four replications. In the second year, all treatments were evenly replicated. At replication level, a spatial correlation structure was added into the model to account for lack of randomization on the assignation of treatments to the plots. Each replication was further divided into transects or locations to account for the light variability across each replication. At the location level, an additional random component was included to account for spatial correlation due to the lack of randomization. To accurately model the collected data, different statistical models were applied based on the measurement structure of each variable. The following section of the article details the models used. The analyses were conducted using the statistical software PROC GLIMMIX (SAS ver. 9.3; SAS Institute Inc., Cary, NC, USA) and R Software (version 4.4.2; R Core Team, Boston, MA, USA) with tailored functions coded in

Fig. 4. Experimental design in 2024: four photovoltaic module (PVB1 to PVB4) and four full sun replicates (FSB1 to FSB4) at the Leyendecker Plant Science Research Center, Las Cruces, NM, USA.

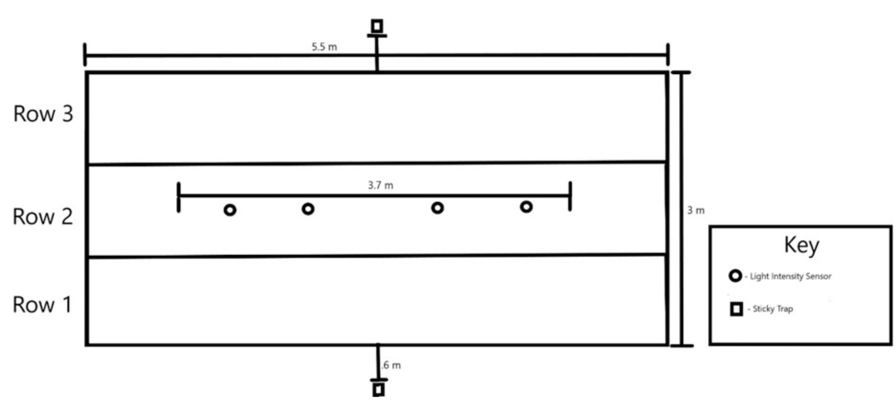

Fig. 5. Diagram of each replicate, 5.5 m long and 3 m wide (16.5 m^2). Rows 1 and 3 were border rows, and the innermost 3.7-m^2 section within row 2 was designated the sample area. Within the sample area, there were four light intensity (lux) sensors (Hobo Pendant MX2202; Onset, Bourne, MA, USA). A yellow sticky trap card for trapping beet leafhoppers measuring 10 cm wide and 25 cm long (250 cm^2) with adhesive was on each side (Pest Trap; Hummert International, Earth City, MO, USA).

Fig. 6. The full sun replications are not shown in this image; however, their sensor setup followed the same configuration. Light sensors (Hobo Pendant MX2202; Onset, Bourne, MA, USA) were positioned at the center of each transect (T1, T2, T3, and T4) within the sample area of each photovoltaic module and full sun replication. Each sensor within the transect is represented by a color-coded rectangle for identification.

Armadillo C++. The latter software was used for Bayesian analyses.

Harvested yield statistical analyses. For all yield variables, except BCTV-affected fruit yields, the model has the following components: treatment, year, and their interaction as fixed effects, while replications are treated as random with spatial correlation to account for lack of randomization (Pinheiro and Douglas 2000). A normal distribution was assumed for all the yield and fruit morphology variables. Because randomization did not occur across years, two random components were included in the model to explain lack of randomization over the levels of the time factor. An extra random effect was included to explain the spatial correlation of the observations collected across locations. The spatial dependences were modeled through an exponential correlation structure, with its corresponding subsample random component (Schabenberger and Gotway 2017). Significant variable means were separated using the Tukey–Kramer test ($P \leq 0.05$), which is used for pairwise comparisons when sample sizes are unequal (Kramer 1956).

The BCTV-affected fruit yields resulted with excess of zeros that cannot be explained by standard models or distributions. The excess zeros occurred because many replications had either BCTV-affected fruit or none at all. To address this, an adapted Student t delta model within a Bayesian framework was implemented. This model includes all the random components described for the other harvested yield categories, except that the BCTV-affected fruit yield is treated as a mixture of distributions to account for the zero inflation (Ridout et al. 1998). Instead of P values, conclusions are drawn from 90% credible intervals, as is standard in Bayesian analysis (Gelman et al. 1995).

Beet leafhopper abundance analysis. The beet leafhopper count data were log-transformed and analyzed using the same experimental design as described for yield. Two sticky traps per replication were monitored, with counts recorded biweekly. To account for temporal correlation, a random effect with an unstructured covariance structure was included in the model (Zuur et al. 2009). Significant variable means were separated using Tukey–Kramer tests ($P \leq 0.05$).

Plant height and basal stem diameter analysis. A three-parameter logistic nonlinear model was used to describe plant measurements and their relationship with time. The model follows a hierarchical structure. At the first level, plant height and basal stem diameter are modeled as a function of time, with the three-parameter logistic model treatment specific. At the second level, the design factors and all previously mentioned random components are incorporated, and the logistic model parameters serve as the response variables (Paine et al. 2012). The parameters of the logistic nonlinear model were: 1) final height, maximum height of the plants at the end of the season; 2) growth rate (slope) of the sigmoidal curve, indicating how quickly the plant grew during the most rapid phase of development; and 3) inflection point, the time at which growth rate is maximized (Thornley and Johnson 1990). The analysis was conducted within a Bayesian framework, with conclusions drawn from 95% credible intervals rather than P values.

Photosynthesis analysis. The net rates of carbon dioxide assimilation data were analyzed with the model for the nonstandard design with treatment, time, date, and their interactions as fixed effects. This response variable was assumed to follow a normal distribution. Replication was included as a random factor with a spatial correlation structure to account for lack of randomization. Because multiple measurements were taken within each date, the time variable distinguishes these observations, effectively creating a split-split-plot design. To account for temporal dependencies, time and date were modeled with a compound symmetry correlation structure (Pinheiro and Douglas 2000).

Results and Discussion

In 2024, the maximum, minimum, and mean air temperatures increased by 0.7, 0.4, and 0.4 °C, respectively, compared with 2023 (Table 1). Overall, the climate in 2024 was warmer and slightly wetter, although the differences were relatively modest.

Light intensity and ambient air temperature. Due to the orientation of the existing field, the PV module shade-covered transects 1, 2, 3, and 4 had varying amounts of shade between 0630 and 1330 HR throughout the season (Fig. 9). The spatial variability in light across replications was accounted for in the statistical analysis. On average, the mean light intensity across all transects was 11% lower in the PV module shaded replications compared with full sun conditions.

Marrou et al. (2013a) investigated the performance of lettuce (*Lactuca sativa*), cucumbers (*Cucumis sativus*), and durum wheat (*Triticum durum* L.) under an agrivoltaic system. In this system, the PV panels provided most of the shade to crops during the morning hours, between 0700 and 1100 HR. In arid climates, the most cumulative photosynthesis typically occurs during the morning

Fig. 7. Students in photovoltaic shaded plot taking photosynthesis measurements (LI-6800; LI-COR Biosciences).

Fig. 8. Harvested fruit categories from full sun and PV module replications in 2023 and 2024. From left to right, 1) marketable green, intact whole unblemished fruit that is at a horticulturally mature green stage and is suitable for market; 2) blossom end rot (BER) affected fruit with BER symptoms, blackened apex; 3) red fruit, intact whole unblemished fruit at ripe red stage; 4) diseased fruit, whole unmarketable fruit that has blemishes and indication of disease; 5) immature fruit, green fruit with malleable pericarps' and 6) beet curly top virus–affected fruit, abnormal block-shaped small fruit caused by curly top virus.

hours (Lambers and Oliveira 2019). Therefore, shading crops during this period may negatively affect growth. However, midday depression of photosynthesis—a decline in photosynthetic rates occurring around midday due to high light intensity and temperature (Yokoyama et al. 2019)—can significantly constrain crop growth and yield potential. To mitigate the effects of midday depression while preserving morning photosynthesis, strategies such as providing selective protection from excessive light and heat can be implemented.

Savalle-Gloire et al. (2022) demonstrated that providing PV-induced shade in the afternoon significantly increased the marketable yield of tomatoes. This finding underscores the importance of optimizing shading strategies to mitigate the adverse effects of high irradiance and temperature on plant physiology. Photosynthetic activity can decline during periods of excessive irradiance, when photosynthesis becomes light saturated and photo-oxidative stress occurs (Chapin et al. 2011). Under such high-light conditions, stomatal conductance is often increased to alleviate carbon dioxide limitations for photosynthesis. This adaptation also results in substantial transpirational water loss, which can be particularly detrimental to plants growing in arid environments characterized by high temperatures and low humidity. To conserve water under these conditions, stomata close, reducing transpiration but concurrently restricting the uptake of carbon dioxide and, consequently, photosynthesis (Chapin et al. 2011).

Shading can modify plant acclimation to such environmental stressors. Plants growing under shaded conditions often exhibit lower photosynthetic capacity per unit leaf area as an adaptive strategy (Lambers and Oliveira 2019). When these shade-adapted plants are suddenly exposed to increased irradiance, their limited photosynthetic capacity restricts their ability to capitalize on the enhanced light availability. These dynamics highlight the complex interplay between light, temperature, water use, and photosynthetic efficiency, particularly in hot, dry, high-light climates, where the balance between water conservation and carbon assimilation is critical for plant productivity.

Table 1. Monthly and season averages of daily maximum, mean, and minimum temperatures and accumulated precipitation during field trials in 2023 and 2024 at Leyendecker Plant Science Research Center, Las Cruces, NM, USA.

Year[i]	Month	Maximum air temperature (°C)	Minimum air temperature (°C)	Mean air temperature (°C)	Precipitation (cm)
2023	May	30.6	10.2	21.0	0.05
	June	34.7	13.8	24.9	0.00
	July	38.0	19.6	29.0	0.03
	August	35.2	19.3	26.9	0.10
	Season average	34.6	15.7	25.5	0.0
2024	May	31.5	8.7	21.1	0.00
	June	37.5	17.4	27.6	0.01
	July	35.8	19.1	27.2	0.12
	August	36.3	19.3	27.7	0.09
	Season average	35.3	16.1	25.9	0.1

[i] Source: ZiaMet Weather Station Leyendecker II Plant Science Research Center (2023 and 2024). 1 cm = 0.3937 inches and 1 °F = (°C × 1.8) + 32.

In this study, shading was restricted to the morning hours due to the fixed orientation of the AVS and the existing field infrastructure. This constraint underscores a critical consideration for farmers and developers when integrating AVS technology into agricultural systems: should modifications to existing infrastructure prioritize maximizing shading for crop production or optimizing energy generation? The orientation and configuration of PV panels play a pivotal role in determining the timing and distribution of shade, which directly influences crop microclimates and, consequently, plant physiological responses.

The limitations inherent in this study highlight the need for adaptive experimental designs. Specifically, reconfiguring the AVS installation to provide afternoon shading would enable a more comprehensive investigation into its impact on crop growth, yield, and physiological responses. Afternoon shading has been demonstrated to mitigate heat stress and enhance productivity in certain crops (Savalle-Gloire et al. 2022). However, the effects afternoon shade remain underexplored across a diverse range of crops, climates, and AVS configurations.

Ambient air temperature. The ambient air temperature underneath the PV modules was observed to be less than the full sun replications, with about a 2% difference in temperature (Fig. 10). Previous studies have reported mixed findings regarding temperature differences in agrivoltaic systems. Some studies observed no significant temperature differences (Marrou et al. 2013b), while others documented measurable variations (Weselek et al. 2019). Factors influencing temperature differences between PV module and full sun replications may include the size, height, and spatial arrangement of the PV modules (Mamun et al. 2022). In this study, the PV system was installed following an open field agrivoltaic design. The setup consisted of four PV modules with a hinge point height of 1.6 m and spaced 12.2 m apart. This configuration was not selected to optimize agrivoltaic performance but rather to enable an initial analysis under practical field conditions.

Beet leafhopper abundance. The interaction between treatment (PV module vs. full sun) and year was not statistically significant ($P = 0.278$), indicating that the effect of the treatment did not vary significantly across different years. Beet leafhopper abundance had consistent patterns under both treatments over the years. The main effect of PV module shade and full sun was significant ($P = 0.023$), with 21% more beet leafhoppers observed in the full sun treatment compared with the PV module–shaded replications (Table 2). This result aligns with previous studies, such as those by Oldfield et al. (1991), which demonstrated that beet leafhoppers exhibit a preference for full sun

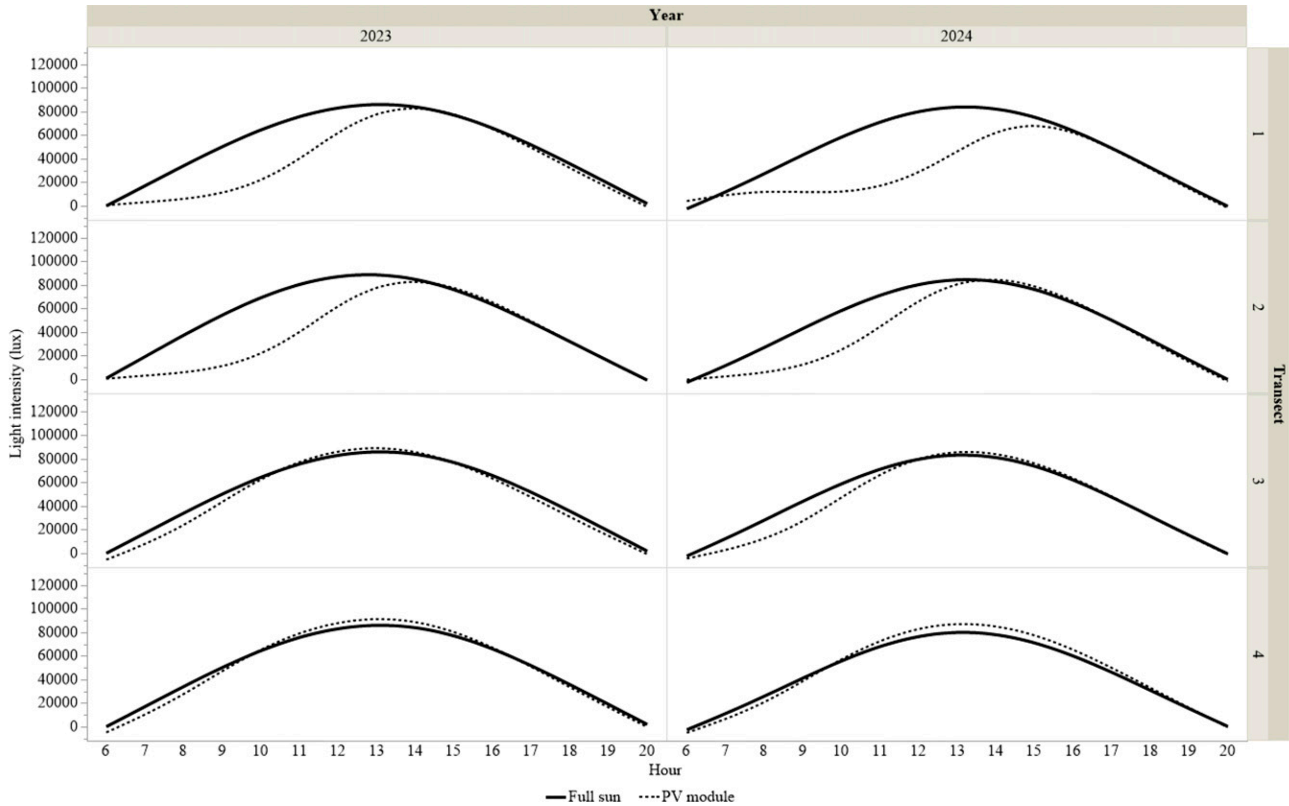

Fig. 9. Hourly light intensity in lux from 0600 and 2000 HR during the 2023 and 2024 seasons for each transect. The hourly means were calculated separately for the full sun and photovoltaic (PV) module replications. The light measurements were logged hourly (Hobo Pendant MX2202; Onset, Bourne, MA, USA) at Leyendecker Plant Science Research Center, Las Cruces, NM, USA.

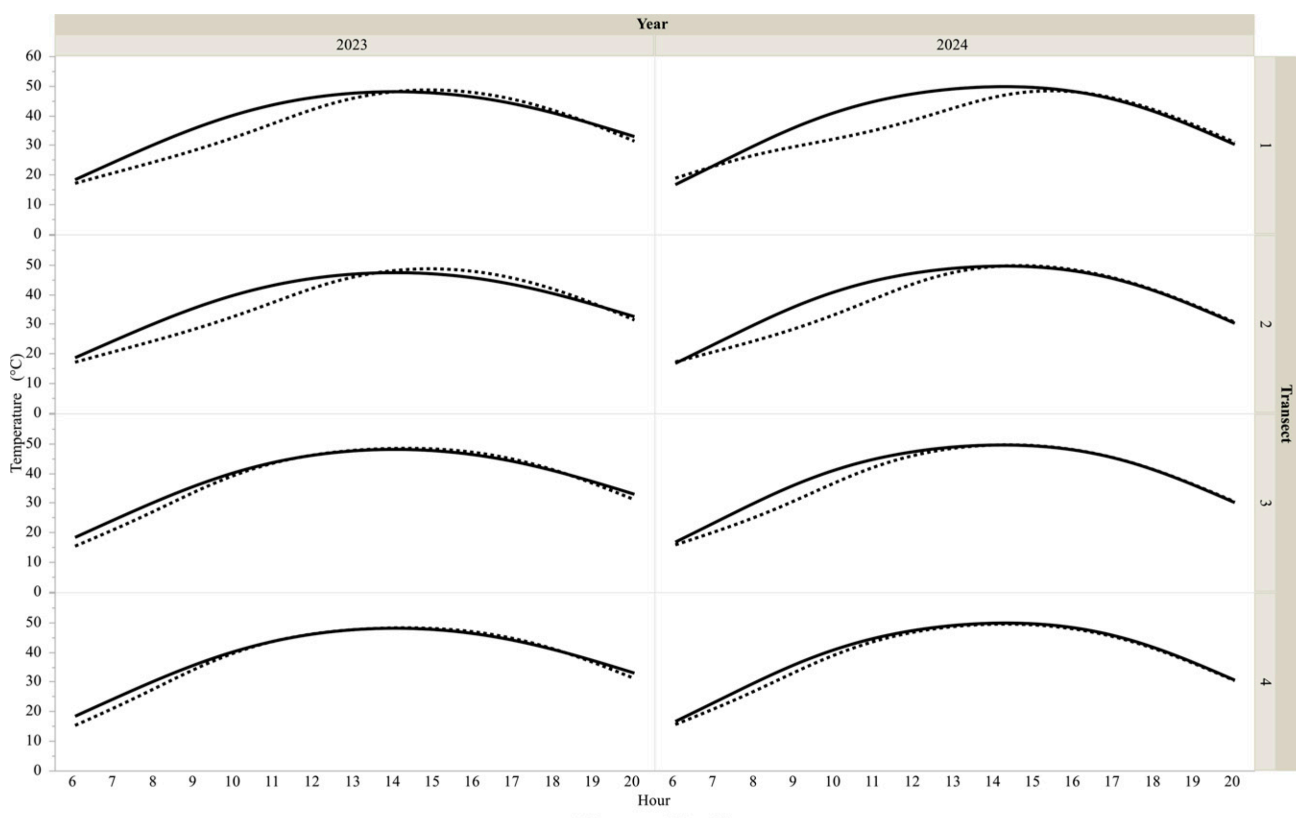

Fig. 10. Hourly temperature (°C) from 0600 and 2000 HR during the 2023 and 2024 seasons for each transect. The hourly means were calculated separately for the full sun and photovoltaic (PV) module replications. The temperature measurements were logged hourly (Hobo Pendant MX2202; Onset, Bourne, MA, USA) at Leyendecker Plant Science Research Center, Las Cruces, NM, USA.

Table 2. Beet leafhopper [*Circulifer* (*Neoaliturus*) *tenellus* Baker] abundance in photovoltaic (PV) module–shaded and full sun replications in 2023 and 2024 at the Leyendecker Plant Science Research Center, Las Cruces, NM, USA.

Variables	Beet leafhopper (count)[i]
Treatment[ii]	
PV module	18 ± 1.2 b[iii]
Full sun	23 ± 1.4 a
Year	
2023	26 ± 1.2 a
2024	14 ± 0.9 b
Interaction	
Treatment × year	NS

[i] Two sticky traps were placed in each replicate and were counted biweekly (five times) throughout the season ($n = 40$ for PV modules in 2023 and 2024; $n = 10$ in 2023 and $n = 40$ in 2024 for full sun replicates).

[ii] The PV module replicates had 11% less light intensity than the full sun replications.

[iii] Means ± standard error followed by the same letter in a column within each effect are not significantly different using the Tukey–Kramer test ($P \leq 0.05$).

NS = nonsignificant.

environments. These findings suggest that the shading provided by PV modules can influence the spatial distribution and movement of pests within agricultural systems, something that has not been identified previously (Walston et al. 2023). This has important implications for pest management strategies, because PV module shade may reduce the need for pesticide applications by discouraging pest activity in shaded areas. Furthermore, this shift in pest behavior could potentially mitigate the spread of pest-associated plant diseases (Cooke et al. 2006). The analysis revealed a significantly higher abundance of beet leafhoppers in 2024 compared with 2023 ($P = 0.001$). This result is consistent with previous research, which has documented seasonal fluctuations in beet leafhopper populations and highlighted their tendency to exhibit considerable interannual variability (Lehnhoff and Creamer 2020).

Photosynthesis. The main effect of year on net carbon dioxide assimilation (A_{net}) was statistically significant ($P = 0.0001$), indicating that A_{net} varied significantly between years. As a result, data from each year were analyzed separately to account for these annual differences. However, the interaction between year × date × time was not significant ($P = 0.392$), suggesting that the temporal patterns of A_{net} across dates and times within each year were consistent and did not differ significantly between years. This implies that while absolute values of A_{net} varied by year, the underlying trends over time were similar across the study period. A significant interaction was observed between treatment (PV module shade vs. full sun) and measurement time (1000, 1100, 1200, and 1300 HR) ($P = 0.017$), indicating that the effect of treatment on A_{net} varied depending on the time of measurement. Pairwise comparisons revealed key differences: at 1000 and 1100 HR, A_{net} was significantly lower in PV module–shaded plants compared with full sun plants ($P = 0.0001$ and 0.038 respectively; Fig. 11). However, at 1200 and 1300 HR, there were no significant differences in A_{net} between the two treatments ($P = 0.077$ and 0.083 respectively; Fig. 11).

Although this is not a complete light response curve (Taiz et al. 2022), the findings provide valuable insight into the photosynthetic response of chile plants cultivated under PV module plots (Busch et al. 2024). Previous studies on bell peppers (*C. annuum*) have reported a diurnal pattern in photosynthesis characterized by an increase in the morning, followed by a slight midday dip and a plateau in the midafternoon (Goo et al. 2024). Our results indicate that shading the chile plants in the morning under PV modules reduces their photosynthetic rate until ∼1100 HR. By 1200 HR, however, the shaded plants are assimilating carbon at a rate comparable to that of chile plants grown in full sun. This observation suggests that the shaded plants may be adapting to the dynamic light environment, optimizing their photosynthetic efficiency across varying light intensities (Lambers and Oliveira 2019). It remains critical, however, to further investigate how afternoon shading influences the photosynthetic dynamics observed in the morning. Additionally, evaluating the extent to which afternoon shading mitigates photoinhibition and thermal stress during periods of intense afternoon radiation will provide a more comprehensive understanding of the benefits and trade-offs associated with PV shading. These findings could have significant implications for optimizing agrivoltaic systems to improve crop productivity and resilience under variable light conditions.

Plant growth measurements. Plant height and basal stem diameter were modeled using a three-parameter logistic nonlinear model to comprehensively capture the dynamics of the growth curve across all developmental stages. This approach allowed for the characterization of key growth parameters, including the final height (maximum plant height at maturity), the growth rate (steepness of the curve during the exponential phase), and the inflection point (time at which the growth rate is maximized). No statistically significant differences were observed in final plant height, growth rate, or inflection point between full sun and PV module–shaded replications in either 2023 or 2024, as indicated by 95% credible intervals (Fig. 12). This suggests that plants in both full sun and PV module–shaded conditions exhibited similar growth rates throughout the study period.

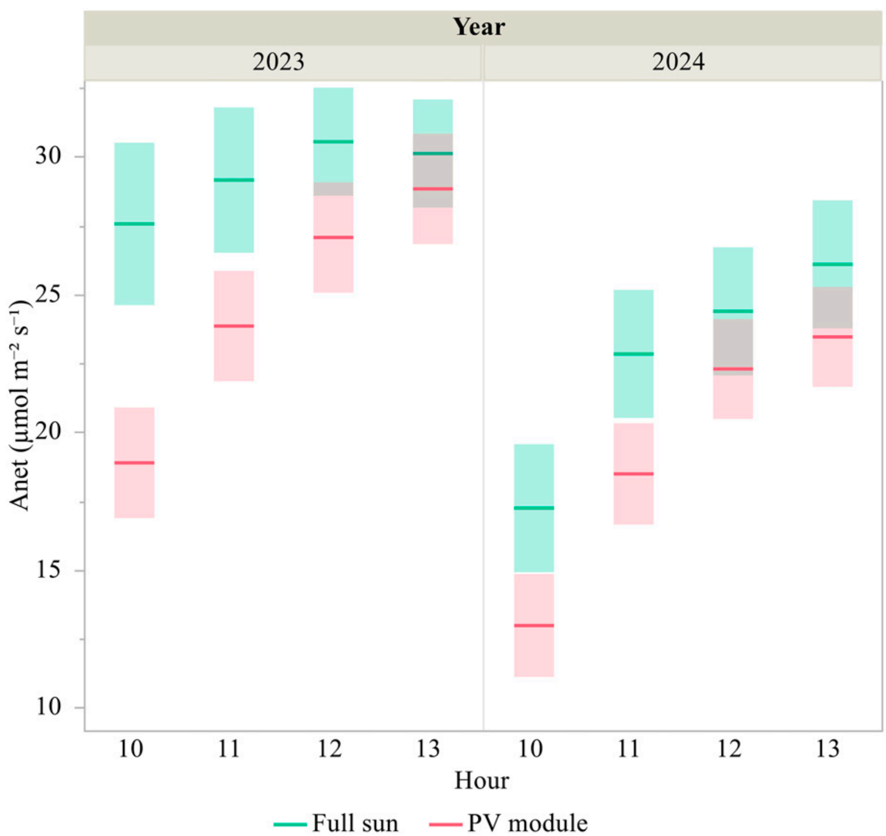

Fig. 11. Mean hourly net carbon dioxide assimilation rates (A_{net}) were measured using an LI-6800 portable photosynthesis system (LI-COR Biosciences), with data presented as means ± standard error bands. Measurements were taken at 1000, 1100, 1200, and 1300 HR on 3 consecutive days in Jul 2023 (10, 12, and 13) and three consecutive days in Jul 2024 (15, 16, and 17). For each time point, A_{net} values were averaged across three chile plants grown under photovoltaic (PV) module shade (n = 48 in 2023 and 2024) and three plants grown in full sun (n = 12 in 2023, and n = 48 in 2024). Time periods with overlapping standard error bands were not significantly different, as determined by the Tukey–Kramer test ($P \leq 0.05$).

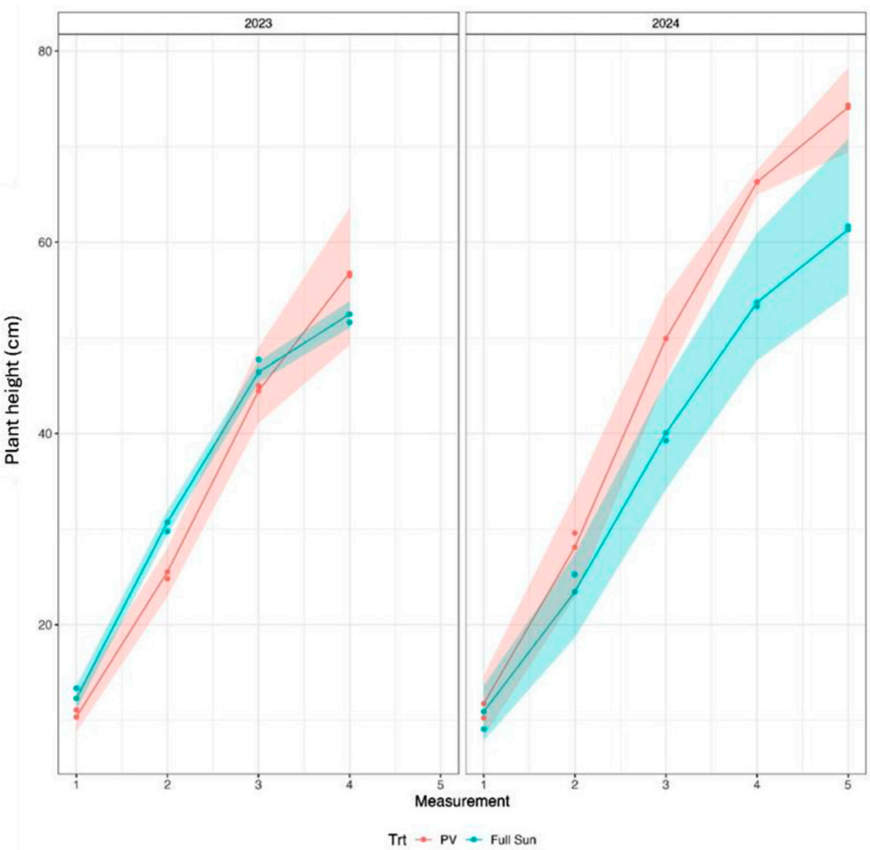

Fig. 12. Plant height (cm) means for four measurement dates in 2023 and five measurement dates in 2024, with measurements taken at 3-week intervals in the photovoltaic module (PV) and full sun treatments (Trt). Height was determined as the vertical distance from the ground level at the base of the plant to the highest point of the plant. Measurements were collected from all 12 plants within each replication. A growth rate curve was generated, incorporating 95% credible interval bands. 1 cm = 0.3937 inches.

These findings contrast with those of Weselek et al. (2021), who reported that plant heights under PV module shading and full sun conditions were initially comparable early in the growing season but diverged later, with shaded plants growing taller in environments with a 30% reduction in photosynthetically active radiation. The phenomenon of taller plants under shaded conditions is often attributed to an increased demand for photosynthates as plants expand, leading to elongation as a strategy to enhance photosynthetic efficiency per unit area under reduced light availability (Díaz-Pérez 2013; Taiz et al. 2022). The absence of such an effect in this study may be explained by the relatively modest 11% reduction in light intensity, coupled with the timing of shading, which occurred exclusively during morning hours. This limited reduction in light intensity may have been insufficient to trigger the elongation response typically observed under more pronounced shading conditions.

Stem diameter, a critical indicator of lodging risk, is an important trait in chile plants (Bosland and Votava 2012). Plants with smaller stem diameters are less capable of supporting heavy fruit loads and are more prone to lodging (McCullough et al. 1993). No statistically significant differences were observed in final basal stem diameter, growth rate, or inflection point between full sun and PV module–shaded replications in either 2023 or 2024, as indicated by 95% credible intervals (Fig. 13). This suggests that chile plants can be grown under PV module shade without an increased risk of lodging due to smaller stem diameters.

Harvested fruit. Statistical analysis revealed that treatment × year interactions were not significant for any of the yield categories evaluated (Table 3). This suggests that the effects of the applied treatments on yield components remained consistent across the study years, with no substantial variation attributable to annual environmental fluctuations or management practices. Among the yield categories, green marketable yield was significantly higher in full sun replicates compared with those under 11% PV module shading ($P = 0.025$). This finding highlights the sensitivity of green chile yield to light availability, as even moderate shading from PV modules had a measurable impact on marketable fruit production. This difference in green yield occurred despite the absence of significant differences in final plant height or basal stem diameter between PV module and full sun replicates (Figs. 12 and 13). This suggests that while vegetative growth parameters were unaffected by shading, reproductive output, specifically the production of marketable green fruits, was compromised under reduced light conditions.

Similar reductions in the marketable yield of bell peppers and jalapeño (*C. annuum*) grown under PV modules have also been documented (Asa'a et al. 2024). Green chile crops grown in New Mexico are well adapted to environments with high light intensity and temperatures (Barchenger and Bosland 2019). Conversely, in Arizona, the yield of 'Chiltepin' (*C. annuum*) was reported to be three times higher under PV systems than in open-field cultivation (Barron-Gafford et al. 2019). This increased yield is likely due to the crop's adaptation to the shaded understory of forests in Mexico (Pickersgill 2016), making it more suitable for shaded environments.

The genetic adaptations of crops play a critical role in their productivity under PV module systems. There is potential for breeding green chile varieties better suited to shaded environments created by PV modules (Pourkheirandish et al. 2020). In this study, the orientation of the PV modules provided shade primarily in the morning. Morning shade coincides with the period when vegetables in hot, arid climates are most photosynthetically active (Lambers and Oliveira 2019). A different yield impact might occur if shade were provided in the afternoon when green chile plants are subject to the highest levels of light and heat stress (Trommsdorff et al. 2022).

In contrast to the significant reduction observed in green marketable yield under PV module shading, other yield categories—including red fruits, fruits affected by BER, diseased fruits, and immature fruits—did not exhibit significant differences between PV module and full sun replicates (Table 3). This suggests that the shading effect was specific to green marketable yield, with no substantial impact on the proportions of nonmarketable yield components. These findings align with previous agrivoltaic studies, which have predominantly focused on marketable yield rather than diseased or nonmarketable yields (Mamun et al. 2022). The absence of significant differences in diseased yields between shaded and full sun replicates is particularly noteworthy, as it indicates that PV module shading does not exacerbate disease incidence in green chile production. This represents a potential benefit for farmers, as it mitigates concerns that reduced light availability might create microclimatic conditions favoring pathogen proliferation. However, the mechanisms underlying this observation remain unclear and warrant further investigation.

The year 2024 demonstrated a significant increase in overall yield across multiple categories (Table 3), including marketable green, red, and BER fruits ($P = 0.002$, 0.05, and 0.01, respectively). This temporal variation in yield performance may be attributed to the higher proportion of full sun replicates in 2024, which increased the overall amount of harvested area.

The yield category of fruits affected by BCTV exhibited significant temporal variability across the study years. In 2024, a statistically significant difference was observed,

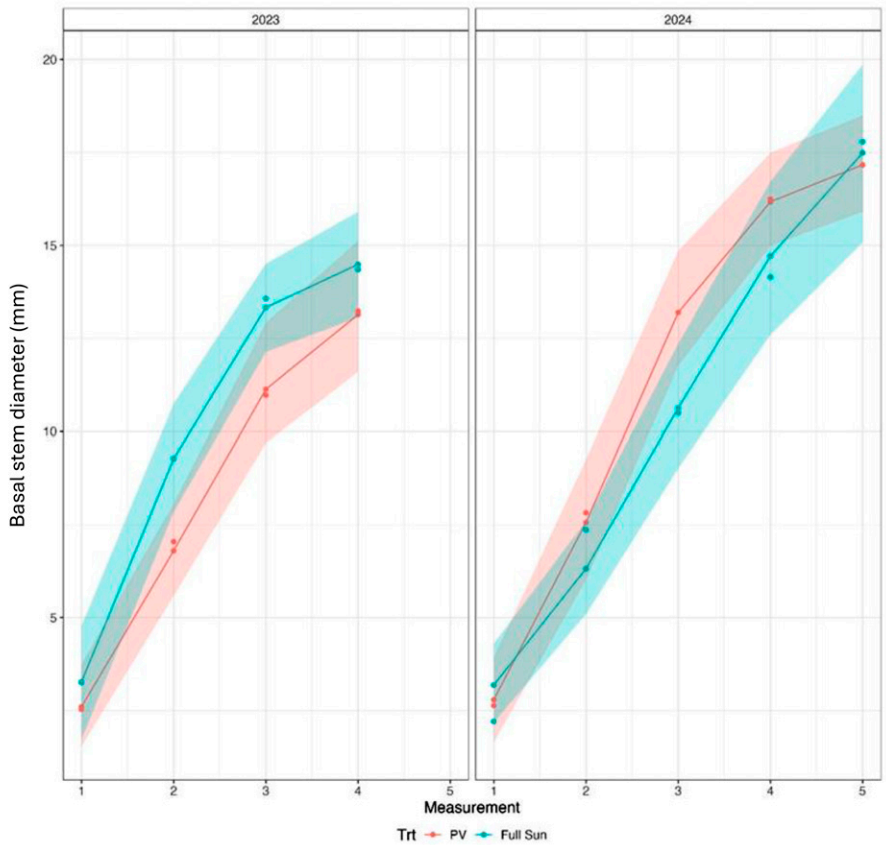

Fig. 13. Basal stem diameter (mm) means for four measurement dates in 2023 and five measurement dates in 2024, with measurements taken at 3-week intervals in the photovoltaic module (PV) and full sun treatments (Trt). Basal stem diameter was measured at the base of the stem directly above ground level using a digital caliper (Absolute Digimatic Caliper; Mitutoyo). Measurements were collected from all 12 plants within each replication. A growth rate curve was generated, incorporating 95% credible interval bands. 1 mm = 0.03937 inches.

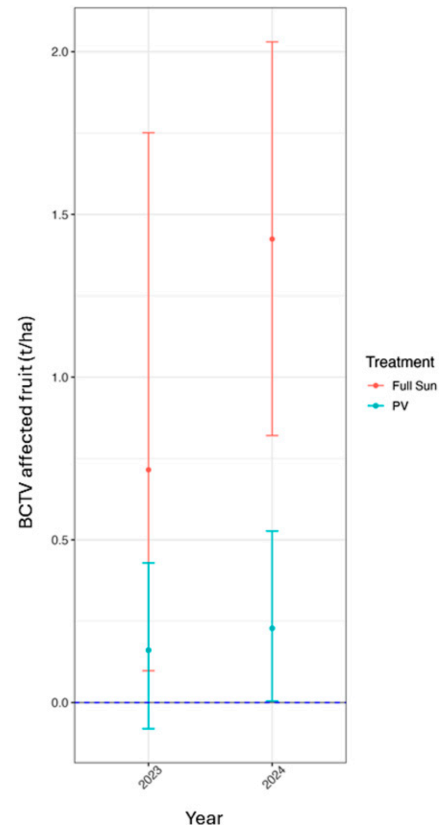

Fig. 14. Beet curly top virus (BCTV) affected 'NuMex Odyssey', a New Mexico pod-type green chile (*C. annuum*) fruit means from photovoltaic (PV) module–shaded and full sun replications in 2023 and 2024 at the Leyendecker Plant Science Research Center, NM, USA. BCTV-affected fruit were abnormal block-shaped small fruit harvested hand harvested on 25 Aug 2023 from four PV module replications and one full sun replication and 29 Aug 2024 from four PV module and full sun replications (replication size, 3.7 m^2). In 2023, there was only one full sun block due to plant death. PV module replications had 11% less light intensity than the full sun replications. The means with 90% credible intervals, overlapping credible intervals are not statistically significant ($P \leq 0.05$).

with full sun replicates demonstrating a higher incidence of BCTV-affected fruit compared with PV module–shaded replicates (Fig. 14). This suggests that environmental or microclimatic conditions associated with full sun exposure may have influenced the prevalence or severity of BCTV infection during this growing season.

Table 3. Yield categories of 'NuMex Odyssey', a New Mexico pod-type green chile (*C. annuum*) in photovoltaic (PV) module–shaded and full sun replications in 2023 and 2024 at the Leyendecker Plant Science Research Center, NM, USA.

	Harvest categories[i] ($t \cdot ha^{-1}$)				
	Marketable green	Red	BER	Diseased	Immature
Treatment[ii]					
PV module	6.1 ± 1.2 b[iii]	3.2 ± 0.4	5.4 ± 0.7	2.7 ± 0.6	0.2 ± 0.1
Full sun	12.1 ± 1.9 a	4.2 ± 1.0	5.7 ± 1.4	2.8 ± 0.3	0.08 ± 0.1
Year					
2023	4.4 ± 1.9 b	2.4 ± 1.0 b	2.9 ± 1.4 b	3.0 ± 0.7	0.02 ± 0.2
2024	13.8 ± 1.2 a	5.0 ± 0.5 a	8.3 ± 0.9 a	2.4 ± 0.4	0.3 ± 0.09
Interaction					
Treatment × year	NS	NS	NS	NS	NS

[i] Harvested fruit categories are as follows: marketable green = intact whole unblemished fruit that is at a horticulturally mature green stage and is suitable for market; red = intact whole unblemished fruit at ripe red stage; blossom end rot (BER) = fruit affected with BER symptoms, blackened apex; diseased = whole unmarketable fruit that has blemishes and indication of disease other than BER and beet curly top virus; immature = green fruit with malleable pericarps. 1 $t \cdot ha^{-1}$ = 0.44609 US ton/acre.

[ii] Fruit was hand harvested on 25 Aug 2023 from four PV module replications and one full sun replication and on 29 Aug 2024 from four PV module and full sun replications (block size: 3.7 m^2). In 2023, there was only one full sun block due to plant death. PV module replications had 11% less light intensity than the full sun replications.

[iii] Means ± standard error followed by the same letter in a column within each effect are not significantly different using the Tukey–Kramer test ($P \leq 0.05$).

NS = nonsignificant.

In contrast, no significant difference in BCTV-affected fruit yield was detected between full sun and PV module replicates in 2023 (Fig. 14). However, a similar trend was observed, with full sun replicates showing a numerically higher incidence of BCTV-affected fruit compared with shaded plots. This consistent pattern across both years, although statistically significant only in 2024, implies that the full sun conditions may create a more favorable environment for BCTV transmission or symptom expression.

This is particularly significant for producers, as BCTV-affected fruit is entirely unmarketable. The observed reduction in beet leafhopper populations and BCTV-affected fruit under PV modules highlights the potential for these systems to serve as an IPM tool. However, further research is necessary to elucidate the underlying mechanisms driving these observations. Key areas of investigation should include the role of microclimatic conditions under PV module shading, such as temperature, humidity, and light intensity, which may influence disease dynamics. Additionally, more in-depth studies on beet leafhopper (*Circulifer tenellus*) behavior, including vector activity and feeding patterns, are essential to understanding BCTV transmission.

Conclusion

The 11% reduction in irradiance caused by PV module shading had a multifaceted impact on green chile production. This reduction significantly affected the marketable green yield, highlighting the sensitivity of green chile crops to light availability, as they are well adapted to high-light and -temperature environments. Additionally, the shading influenced the prevalence of BCTV-affected fruit, with a reduction observed under PV modules in 2024. This suggests that shading could play a role in mitigating the impact of BCTV, a critical factor for producers as BCTV-affected fruits are entirely unmarketable.

Moreover, the lower irradiance was associated with a decrease in beet leafhopper abundance, the primary vector for BCTV. This finding underscores the potential of PV modules not only as an energy generation tool but also as an IPM strategy. By reducing pest populations and disease prevalence, PV module shading can contribute to improved crop health and reduced reliance on chemical controls, enhancing sustainability in agricultural practices.

While the reduced irradiance posed challenges to marketable green chile yield, the observed benefits in pest and disease management highlight opportunities to optimize production systems under PV module shading. Additionally, increasing shading in the afternoon, when plant stress from light and heat is at its peak, could potentially improve green chile yields by alleviating environmental stress. Future research should prioritize identifying the optimal timing and intensity of shading for chile growth under PV systems. Studies should also assess the impact of PV shading on critical factors such as flavor profiles, water use efficiency, and the development of green chile varieties specifically bred for shaded environments. Furthermore, a comprehensive evaluation of the long-term economic and ecological trade-offs of integrating PV systems into agricultural landscapes is necessary. Such research will guide the development of sustainable production practices that balance energy generation, crop yield, and environmental stewardship when integrating photovoltaic panels into agricultural production fields.

References Cited

Asa'a S, Reher T, Rongé J, Diels J, Poortmans J, Radhakrishnan HS, van der Heide A, Van de Poel B, Daenen M. 2024. A multidisciplinary view on agrivoltaics: Future of energy and agriculture. Renewable Sustain Energy Rev. 200: 114515. https://doi.org/10.1016/j.rser.2024.114515.

Barchenger DW, Bosland PW. 2019. Wild chile pepper (*Capsicum* L.) of North America, p 225–242. In: Greene SL, Williams KA, Khoury CK, Kantar MB, Marek LF (eds). North American crop wild relatives, volume 2. Springer International Publishing, Cham, Switzerland. https://doi.org/10.1007/978-3-319-97121-6_7.

Barron-Gafford GA, Pavao-Zuckerman MA, Minor RL, Sutter LF, Barnett-Moreno I, Blackett DT, Thompson M, Dimond K, Gerlak AK, Nabhan GP, Macknick JE. 2019. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nat Sustain. 2(9): 848–855. https://doi.org/10.1038/s41893-019-0364-5.

Bosland P, Votava E. 2012. Peppers: Vegetable and spice capsicums (2nd ed). CABI Publishing, Cambridge, MA, USA.

Bosland P, Walker S. 2014. Growing chiles in New Mexico. New Mex State Univ Agric Exp Sta Guide H-230. https://pubs.nmsu.edu/_h/H230.pdf. [accessed 15 Apr 2024].

Busch FA, Ainsworth EA, Amtmann A, Cavanagh AP, Driever SM, Ferguson JN, Kromdijk J, Lawson T, Leakey ADB, Matthews JSA, Meacham-Hensold K, Vath RL, Vialet-Chabrand S, Walker BJ, Papanatsiou M. 2024. A guide to photosynthetic gas exchange measurements: Fundamental principles, best practice and potential pitfalls. Plant Cell Environ. 47(9):3344–3364. https://doi.org/10.1111/pce.14815.

Chapin FS, Matson PA, Vitousek PM. 2011. Principles of terrestrial ecosystem ecology. Springer, New York, NY, USA. https://doi.org/10.1007/978-1-4419-9504-9.

Cooke BM, Jones DG, Kaye B (eds). 2006. The epidemiology of plant diseases. Kluwer Academic Publishers, Dordrecht, Netherlands. https://doi.org/10.1007/1-4020-4581-6.

Crawford RF. 1927. Curly top in New Mexico. US Dept Agric Resour Publ. 6(8):2.

Creamer R. 2003. Incidence of the beet leafhopper, *Circulifer tenellus* (Homoptera: Cicadellidae) in New Mexico chile. Southwestern Entomol. 28(3):177–182.

Creamer R, Carpenter J, Rascon J. 2004. Incidence of the beet leafhopper in New Mexico chile. New Mex State Univ Agric Exp Sta Rep. 12. https://pubs.nmsu.edu/research/horticulture/CTF12/. [accessed 18 Apr 2024].

Creamer R, Sanogo S, El-Sebai OA, Carpenter J, Sanderson R. 2005. Kaolin-based foliar reflectant affects physiology and incidence of beet curly top virus but not yield of chile pepper. HortScience. 40(3):574–576. https://doi.org/10.21273/HORTSCI.40.3.574.

Dent D, Binks RH. 2020. Insect pest management (3rd ed). CABI Publishing, Cambridge, MA, USA.

Díaz-Pérez JC. 2013. Bell pepper (*Capsicum annum* L.) crop as affected by shade level: Microenvironment, plant growth, leaf gas exchange, and leaf mineral nutrient concentration. HortScience. 48(2):175–182. https://doi.org/10.21273/HORTSCI.48.2.175.

Food and Agriculture Organization. 2022a. FAO's plant production and protection division. United Nations. https://doi.org/10.4060/cc2447en. [accessed 18 Apr 2024].

Food and Agriculture Organization. 2022b. Pesticides use, pesticides trade and pesticides indicators. United Nations. https://openknowledge.fao.org/server/api/core/bitstreams/78705276-3455-4c70-ac77-3082095f83b3/content. [accessed 18 Apr 2024].

Gelman A, Carlin JB, Stern HS, Rubin DB. 1995. Bayesian data analysis. Chapman and Hall/CRC, New York, NY, USA.

Goetzberger A, Zastrow A. 1982. On the coexistence of solar-energy conversion and plant cultivation. Int J Solar Energy. 1(1):55–69. https://doi.org/10.1080/01425918208909875.

Goldberg N. 1995. Chile pepper diseases. New Mex State Univ Agr Exp Sta Cir 549. https://pubs.nmsu.edu/_circulars/CR549/. [accessed 18 Apr 2024].

Goo H, Roh Y, Lee J, Park KS. 2024. Analysis of bell pepper (*Capsicum annuum* L.) leaf spectral properties and photosynthesis according to growth period. Horticulturae. 10(6):646. https://doi.org/10.3390/horticulturae10060646.

Graham M, Ates S, Melathopoulos AP, Moldenke AR, DeBano SJ, Best LR, Higgins CW. 2021a. Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. Sci Rep. 11(1):7452. https://doi.org/10.1038/s41598-021-86756-4.

Graham M, Best L, Moldenke AR. 2021b. Digital record of specimens, including voucher material, from the study of a pollinator habitat restoration site under a commercial solar array in Jackson County, Oregon, 2019. Cat OR State Arth Coll. 5(2). https://doi.org/10.5399/osu/cat_osac.5.2.4855.

Grodsky SM, Campbell JW, Hernandez RR. 2021. Solar energy development impacts flower-visiting beetles and flies in the Mojave desert. Biol Conservation. 263:109336. https://doi.org/10.1016/j.biocon.2021.109336.

Kogan M. 1998. Integrated pest management: Historical perspectives and contemporary developments. Annu Rev Entomol. 43:243–270. https://doi.org/10.1146/annurev.ento.43.1.243.

Kramer CY. 1956. Extension of multiple range tests to group means with unequal numbers of replications. Biometrics. 12(3):307–310. https://doi.org/10.2307/3001469.

Lambers H, Oliveira R. 2019. Plant physiological ecology (3rd ed). Springer Publishing, Princeton, NJ, USA.

Lehnhoff E, Creamer R. 2020. Prediction of early season beet leafhopper populations in southern New Mexico. Plant Health Prog. 21(1):71–76. https://doi.org/10.1094/PHP-08-19-0051-FI.

Lillywhite J, Robinson C. 2023. Understanding chile pepper consumers' preferences: A discrete choice experiment. Agriculture. 13(9):1792. https://doi.org/10.3390/agriculture13091792.

Macknick J, Hartmann H, Barron-Gafford G, Beatty B, Burton R, Seok-Choi C, Davis M, Davis R, Figueroa J, Garrett A, Hain L, Herbert S, Janski J, Kinzer A, Knapp A, Lehan M, Losey J, Marley J, MacDonald J, McCall J, Nebert L, Ravi S, Schmidt J, Staie B, Walston L. 2022. The 5 Cs of agrivoltaic success factors in the United States: Lessons from the InSPIRE research study. Natl Renewable Energy Lab. https://doi.org/10.2172/1882930.

Mamun MAA, Dargusch P, Wadley D, Zulkarnain NA, Aziz AA. 2022. A review of research on agrivoltaic systems. Renewable Sustain Energy Rev. 161:112351. https://doi.org/10.1016/j.rser.2022.112351.

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 Meterol. 177:117–132. https://doi.org/10.1016/j.agrformet.2013.04.012.

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. https://doi.org/10.1016/j.eja.2012.08.003.

McCullough MD, Motes JE, Kahn BA, Maness NE. 1993. Lodging in direct seeded peppers.

HortScience. 28(4):268–269. https://doi.org/10.21273/HORTSCI.28.4.268G.

National Resources Conservation Services. 2024. Web soil survey. https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx. [accessed 9 Apr 2024].

Oldfield GN, Yokomi RK, Golino DA, Gumpf DJ. 1991. Flight phenology of *Circulifer tenellus* and other leafhoppers in San Joaquin Valley citrus groves. Int Organ Citrus Virologists Conf Proc (1957–2010). 11(11). https://doi.org/10.5070/C51rn9h32m.

Paine CET, Marthews TR, Vogt DR, Purves D, Rees M, Hector A, Turnbull LA. 2012. How to fit nonlinear plant growth models and calculate growth rates: An update for ecologists. Methods Ecol Evol. 3(2):245–256. https://doi.org/10.1111/j.2041-210X.2011.00155.x.

Pickersgill B. 2016. Chile peppers (*Capsicum* spp.), p 417–437. In: Lira R, Casas A, Blancas J (eds). Ethnobotany of Mexico: Interactions of people and plants in Mesoamerica. Springer, New York, NY, USA. https://doi.org/10.1007/978-1-4614-6669-7_17.

Pinheiro J, Douglas B. 2000. Mixed-effects models in S and S-PLUS. Springer-Verlag, New York City, NY, USA. https://doi.org/10.1007/b98882.

Pourkheirandish M, Golicz AA, Bhalla PL, Singh MB. 2020. Global role of crop genomics in the face of climate change. Front Plant Sci. 11:922. https://doi.org/10.3389/fpls.2020.00922.

Ridout M, Demétrio CG, Hinde J. 1998. Models for count data with many zeros, p 179–192. Proceedings of the XIXth International Biometric Conference. International Biometric Society Invited Papers Cape Town, South Africa.

Savalle-Gloire N, Vercambre G, Chopard J, Blanchard-Gros R, Catala J, Fumey D, Gautier H. 2022. Transient shading effect on tomato yield in plastic greenhouse. AIP Conf Proc. 2635(1): 090002. https://doi.org/10.1063/5.0106050.

Schabenberger O, Gotway CA. 2017. Statistical methods for spatial data analysis. Chapman and Hall/CRC, New York, NY, USA. https://doi.org/10.1201/9781315275086.

Taiz L, Møller IM, Murphy A, Zeiger E. 2022. Plant physiology and development (7th ed). Oxford University Press, New York, NY, USA.

Thornley JH, Johnson IR. 1990. Plant and crop modelling. Blackburn Press, Caldwell, NJ, USA.

Trommsdorff M, Dhal IS, Özdemir ÖE, Ketzer D, Weinberger N, Rösch C. 2022. Agrivoltaics: Solar power generation and food production, p 159–210. In: Gorjian S, Campana PE (eds). Solar energy advancements in agriculture and food production systems. Academic Press, San Diego, CA, USA. https://doi.org/10.1016/B978-0-323-89866-9.00012-2.

US Department of Agriculture, National Agricultural Statistics Service. 2023. 2023 New Mexico chile production. https://www.nass.usda.gov/Statistics_by_State/New_Mexico/Publications/Special_Interest_Reports/NM-2023%20Chile%20Production.pdf. [accessed 9 Apr 2024].

US Department of Agriculture. 2018. A national road map for integrated pest management. https://www.ars.usda.gov/arsuserfiles/opmp/ipm%20road%20map%20final.pdf. [accessed 9 Apr 2024].

Walker SJ, Funk P, Joukhadar I, Place T, Havlik C, Tonnessen B. 2021. ‘NuMex Odyssey’, a New Mexico–type green chile pepper for mechanical harvest. HortScience. 56(12):1605–1607. https://doi.org/10.21273/HORTSCI15793-21.

Walston LJ, Hartmann HM, Fox L, Macknick J, McCall J, Janski J, Jenkins L. 2023. If you build it, will they come? Insect community responses to habitat establishment at solar energy facilities in Minnesota, USA. Environ Res Lett. 19:014053. https://doi.org/10.1088/1748-9326/ad0f72.

Wechsler SJ. 2023. With domestic chili pepper production cooling off, imports have heated up. US Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/data-products/charts-of-note/chart-detail?chartId=107365. [accessed 9 Apr 2024].

Weselek A, Bauerle A, Zikeli S, Lewandowski I, Högy P. 2021. Effects on crop development, yields and chemical composition of celeriac (*Apium graveolens* L. var. rapaceum) cultivated underneath an agrivoltaic system. Agronomy. 11(4):733. https://doi.org/10.3390/agronomy11040733.

Weselek A, Ehmann A, Zikeli S, Lewandowski I, Schindele S, Högy P. 2019. Agrophotovoltaic systems: Applications, challenges, and opportunities. Agron Sustain Dev. 39(4):35. https://doi.org/10.1007/s13593-019-0581-3.

Yokoyama G, Yasutake D, Tanizaki T, Kitano M. 2019. Leaf wetting mitigates midday depression of photosynthesis in tomato plants. Photosynthetica. 57(3):740–747. https://doi.org/10.32615/ps.2019.088.

Zuur AF, Ieno EN, Walker N, Saveliev AA, Smith GM. 2009. Mixed effects models and extensions in ecology with R. Springer, New York, NY, USA. https://doi.org/10.1007/978-0-387-87458-6.