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Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands

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The vulnerabilities of our food, energy and water systems to projected climatic change make building resilience in renewable energy and food production a fundamental challenge. We investigate a novel approach to solve this problem by creating a hybrid of colocated agriculture and solar photovoltaic (PV) infrastructure. We take an integrative approach—monitoring microclimatic conditions, PV panel temperature, soil moisture and irrigation water use, plant ecophysiological function and plant biomass production within this 'agrivoltaics' ecosystem and in traditional PV installations and agricultural settings to quantify trade-offs. We find that shading by the PV panels provides multiple additive and synergistic benefits, including reduced plant drought stress, greater food production and reduced PV panel heat stress. The results presented here provide a foundation and motivation for future explorations towards the resilience of food and energy systems under the future projected increased environmental stress involving heat and drought.

A key challenge to building resilience under a changing and uncertain climate is maintaining and improving both energy and food production security. Such efforts are hampered, in part, by conventional understanding of land use that asserts an inherent 'zero-sum-game' of competition between some forms of renewable energy—particularly solar PV installations—and agricultural food production. While some farms have adopted renewable energy production to assist with their function[1], this either–or discourse drives many policies and development decisions around conservation practices, land and water allotments for agriculture, and permitting the establishment of large-scale renewable energy installations[2–5]. However, we may require a more holistic and integrated approach centred at the nexus of food, energy and water system studies that simultaneously meets increasing energy demands through decentralized technologies, reduces impacts from the land use footprint of energy development or immobilization of land resources for biofuel production (termed 'energy sprawl'[6]) and addresses the need for more efficient food production in diverse landscapes, all while minimizing water use and environmental impacts[7–10]. This type of nexus thinking and research emphasizes links among water, energy and food resource systems and extends beyond single-sector approaches to resource management[11,12].

Globally, our food systems are vulnerable to projected changes in climate—primarily changes in the timing and amount of precipitation and rising air temperatures[13,14]. We grow non-dryland-adapted food within a dryland climate through an over-reliance on irrigation[15,16], and models predict a northward migration in potential rain-fed agricultural areas based on projected climate change[17]. In fact, within the United States, water scarcity alone was a major driver in the conversion of more than 20,000 acres of former croplands in southern California to renewable energy development in a single year[18], as the lack of water was making agriculture non-economically viable. Many areas across the globe, including North, Central, and South America, the Middle East and North Africa, have seen a shift to increased aridity and are projected to see continued aridity throughout the century[19,20]. These regions are also facing increasing water scarcity that places conventional agriculture and farmland at risk, and projected climate change has been estimated to reduce food production by 8–45% across Africa and Southeast Asia[21–24]. The resulting increases in demand for irrigation will probably compound existing water insecurities experienced globally. Our already strained freshwater supply is likely to see additional extraction, not only for future agricultural land use to keep pace with population and economic growth, but also to match the increased atmospheric demand under these projected climate changes[25].

Our energy system may not be resilient under forecasted climate change[26]. Higher air temperatures can reduce the efficiency and maximum capacity of thermal power plants[27,28], and changes in the seasonality, availability and temperature of water resources can constrain the operations of hydropower[29–31] and thermal power plants[32–34]. Globally climate impacts could reduce thermal and hydropower capacity by 20% for individual power plants[35–37], although grid reliability metrics indicate a smaller impact[38]. Drought-proof technologies that require no water for operations, such as wind and PV, could provide a solution for enhanced resilience under uncertain water resource conditions while also cutting down on greenhouse gases emission—a primary cause of climate change.

Electricity production from large-scale PV installations has increased exponentially in recent decades[4,39,40], signifying an increase in the cost-effectiveness and grid suitability of this technology[2,41]. In the United States, solar development is projected to grow substantially. By 2030, solar installation could reach 330 GW of installed

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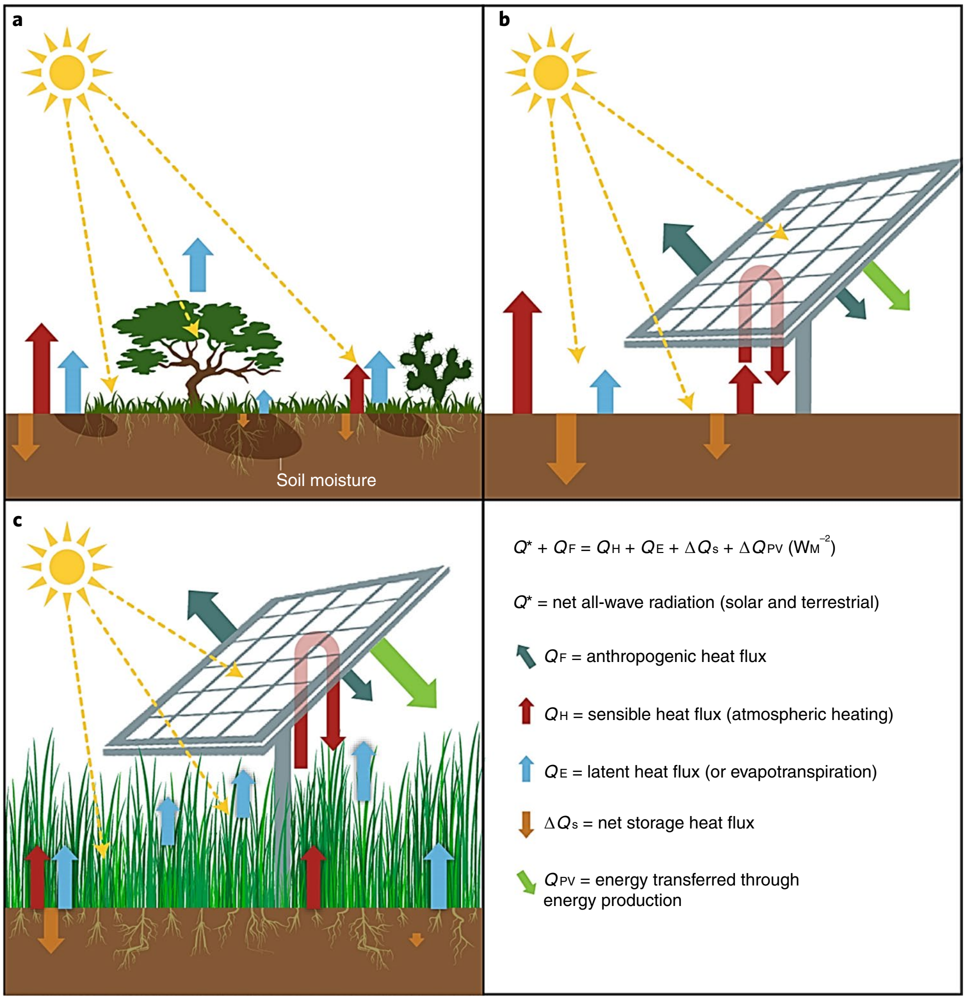

Fig. 1 | Illustration of changes in midday energy exchange with transitions from natural systems, solar PV arrays and a colocated agrivoltaic system. **a**,**b**, Assuming equal rates of incoming energy from the sun (broken yellow arrows), a transition from a vegetated ecosystem (**a**) to a solar PV installation (**b**) will significantly alter the energy flux dynamics of the area because of the removal of vegetation, and thus the latent heat fluxes (blue arrows). This leads to greater sensible heat fluxes (red and orange arrows), which yield higher localized temperatures. **c**, Reintroduction of vegetation, in this case agricultural plants, restores latent heat fluxes and should reduce sensible heat loss to the atmosphere. Energy re-radiation from PV panels (teal arrows) and energy transferred to electricity (green arrows) are also shown. Arrow size and abundance correspond to the magnitude of the effect. Credit: Illustration modified from ref. [49], Springer Nature Ltd.

capacity (to meet 14% of national demands), with 209 GW expected to be ground-mounted solar, which would require approximately 8,000 km^2 of land, including agricultural land[42,43].

Drylands of the southwestern United States are among the best positioned for supporting renewable energy through PV because of the abundance of sunlight[44,45], but projections of increasing ambient temperatures dampen this renewable energy source potential because of PV panel sensitivity to increases in temperature. While PV panels vary, their temperature coefficient—the rate of performance decline for every 1 °C increase in temperature >25 °C—illustrates that PV panel efficiency decreases by an average of ~0.6% °C^{-1})[46–48]. Additionally, recent research has found that larger PV arrays cause a 'heat island' effect that warms the area within the installations[49], creating a negative feedback of additional warming. As with the urban heat island effect, landscape change shifts ecosystem structure from one dominated by vegetation to one characterized by a blend of built structures and vegetation, which alters the energy balance of absorption, storage and release of short- and long-wave radiation[50]. Incoming solar energy is either reflected back to the atmosphere or absorbed, stored and later re-radiated in the form of latent or sensible heat[51] (Fig. 1, blue or red and orange arrows, respectively). Within natural ecosystems, vegetation reduces heat gain and storage in soils by creating surface shading, though the degree of shading varies among plant types (Fig. 1a)[52]. Transitions of liquid water-to-water vapour loss to the atmosphere through evapotranspiration—the combined water loss from soils (evaporation) and vegetation (transpiration)—use energy absorbed by vegetation and surface soils. Because many PV installations have gravel as groundcover, with little to no vegetation, they have little to no means of energy dissipation through latent heat exchange (Fig. 1, transition from a to b), and thus are subjected to more sensible heat.

Sustainable development practices of low-impact urban design counter the urban heat island effect with strategic planting that reintroduces latent heat exchange of energy by way of plant transpiration. How might a similar model be applied to a PV heat island? Restoration ecology suggests that there is an important role for 'novel ecosystems'—non-historical assemblages of species that result from the combined effects of shifts in abiotic conditions, land cover change and environmental management[53]. Novel ecosystems serve important functional roles, contribute to the provision of ecosystem services and enhance well-being in human-dominated and built landscapes[54,55].

We present here a novel ecosystems approach—agrivoltaics—to bolster the resilience of renewable energy and food production security to a changing climate by creating a hybrid of colocated agriculture and solar PV infrastructure, where crops are grown in the partial shade of the solar infrastructure[12,41,56–66] (Fig. 1c). We suggest that this energy- and food-generating ecosystem may become an important—but as yet quantitatively uninvestigated—mechanism for maximizing crop yields, efficiently delivering water to plants and generating renewable energy in dryland environments. We demonstrate proof of concept for agrivoltaics as a food–energy–water system approach in drylands by simultaneously monitoring the physical and biological dimensions of the novel ecosystem. We hypothesized that colocating solar and agricultural could yield several significant benefits to multiple ecosystem services, including (1) water: maximizing the efficiency of water used for plant irrigation by decreasing evaporation from soil and transpiration from crop canopies[49,67] and (2) food: preventing depression in photosynthesis due to heat and light stress[57,68,69], thus allowing for greater carbon uptake for growth and reproduction. An additional benefit might be (3) energy: transpirational cooling from the understorey crops lowering temperatures on the underside of the panels, which could improve PV efficiency[49].

We focused on three common agricultural species that represent different adaptive niches for dryland environments: chiltepin pepper (*Capsicum annuum* var. *glabriusculum*), jalapeño (*C. annuum* var. *annuum*) and cherry tomato (*Solanum lycopersicum* var. *cerasiforme*). We created an agrivoltaic system by planting these species under a PV array—3.3 m off the ground at the lowest end and at a tilt of 32°—to capture the physical and biological impacts of this approach. Throughout the average three-month summer growing season we monitored incoming light levels, air temperature and relative humidity continuously using sensors mounted 2.5 m above the soil surface, and soil surface temperature and moisture at 5-cm depth. Both the traditional planting area (control) and agrivoltaic system received equal irrigation rates, and we tested two irrigation scenarios—daily irrigation and irrigation every 2 d.

Results

The amount of incoming photosynthetically active radiation (PAR) was consistently greater in the traditional, open-sky planting area (control plot) than under the PV panels (Fig. 2a). This reduction in the amount of incoming energy under the PV panels yielded cooler daytime air temperatures, averaging 1.2 + 0.3 °C lower in the agrivoltaics system over the traditional setting. Night-time temperatures were 0.5 + 0.4 °C warmer in the agrivoltaics system over the traditional setting (Fig. 2b). Photosynthetic rates, and therefore growth and reproduction, are also regulated by atmospheric dryness, as represented by vapour pressure deficit (VPD) where lower VPD indicates more moisture in the air. VPD was consistently lower in the agrivoltaics system than in the traditional growing setting, averaging 0.52 + 0.15 kPa lower across the growing season (Fig. 2c). Having documented that an agrivoltaic installation can significantly reduce air temperatures, direct sunlight and atmospheric demand for water relative to nearby traditional agricultural settings, we address several questions regarding impacts of the food–energy–water nexus system.

Potential impacts for food production. We found that agrivoltaic system conditions impacted every aspect of plant activity, though results and significance varied by species. We used three different agricultural plants from the same family (Solanaceae) that represent different adaptive niches for dryland environments (Fig. 3). *Capsicum annuum* var. glabriusculum is native to southern North America and northern South America, and has the adaptation of growing in the shade of overstorey 'nurse trees' due to the high irradiance and temperatures characteristic of the region[70]. Cumulative CO_2 uptake in chiltepin was 33% greater in the agrivoltaic installation (Fig. 3a), but there was no difference in the water use efficiency (ratio of daily CO_2 uptake to transpirational water loss) of the plants (Fig. 3b), indicating that transpiration was equally greater in chiltepin grown in the agrivoltaic system. As a result, total chiltepin fruit production was three times greater under the PV panels in an agrivoltaic system (Fig. 3c). This matches the adaptation of this small-leaved desert shrub and previous studies growing chiltepin under artificial shade (but not in an agrivoltaic system)[70]. We also chose *C. annuum* var. *annuum*), a sister variety to chiltepin that has been widely domesticated across large biogeographic space and is of greater commercial value[71]. Cumulative CO_2 uptake in jalapeño was 11% lower in the agrivoltaic system than in the traditional growing area (Fig. 3a), suggesting a light limitation in this setting. However, water use efficiency was 157% greater in the agrivoltaic system (Fig. 3b). Ultimately, total fruit production was nearly equal between treatments (Fig. 3c), but this was attained with 65% less transpirational H_2O loss. Finally we chose *S. lycopersicum* var. *cerasiforme*) because it is very heat sensitive, in that summer flower production is accompanied by abortion due to excessive temperatures. Cumulative CO_2 uptake was 65% greater in the agrivoltaic installation than in the traditional growing area, and water use efficiency was also 65% greater, indicating that transpirational water loss was equal between the treatment areas, so the increased productivity we find in an agrivoltaic system is probably due to an alleviation of multiple stress interactions from heat and atmospheric drought. Ultimately, total fruit production was twice as great under the PV panels of the agrivoltaic system than in the traditional growing environment.

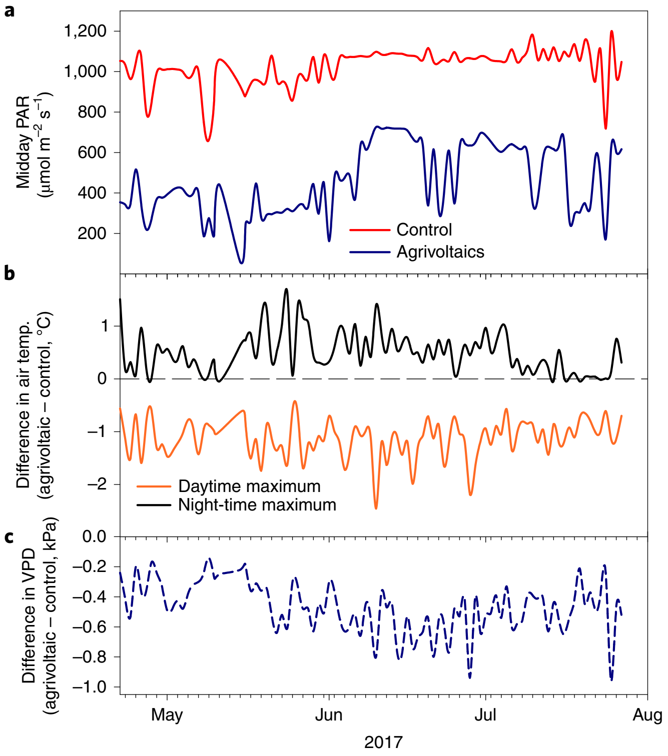

Fig. 2 | Micrometeorological impacts of colocation of agriculture and solar PV panels (agrivoltaic) over traditional (control) installations. a, Average daily light levels in terms of PAR. **b**, Differences in ambient air temperature between daytime and night-time. **c**, Atmospheric dryness, VPD.

Potential impacts for water savings. We assessed the impacts of irrigation water savings in terms of the relative amount of moisture

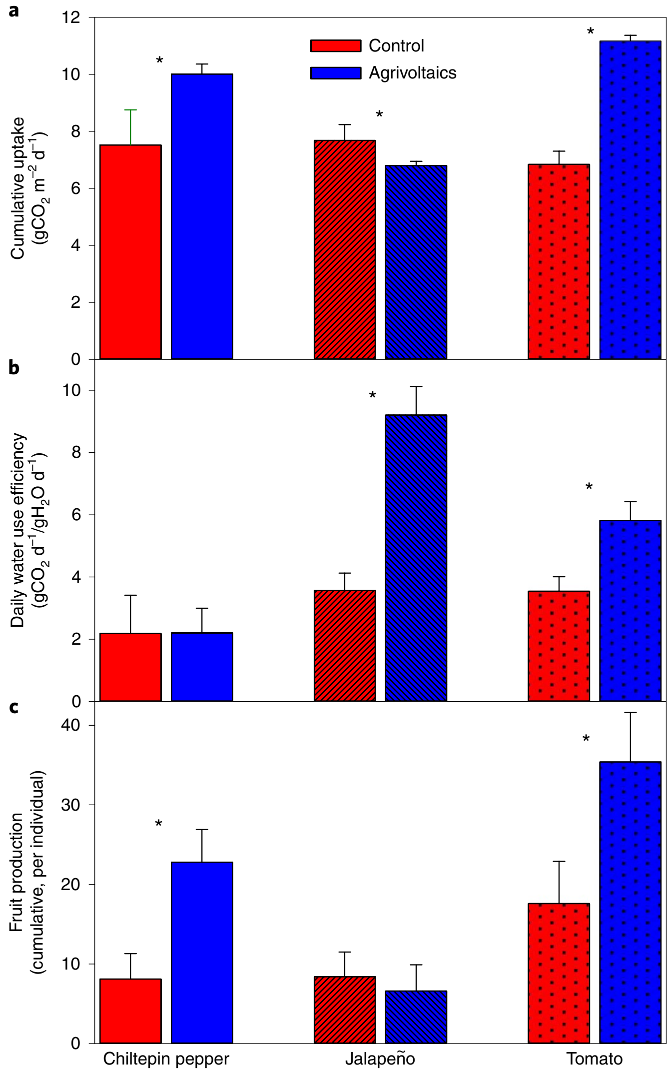

Fig. 3 | Plant ecophysiological impacts of colocation of agriculture and solar PV panels versus traditional installations. a, Average daily cumulative CO uptake through photosynthesis per unit leaf area. **b**, Daily water use efficiency, as estimated by the amount of carbon uptake relative toleaf-level water loss through transpiration (per unit leaf area). **c**, Cumulative fruit production—number of fruits per individual plant. Results are shown for chiltepinpeppers, jalapeños and tomatoes grown in a traditional setting (control) and in the colocated agrivoltaics system. Bars represent +1 s.e.m., and an asterisk indicates a significant difference ($P<0.001$).

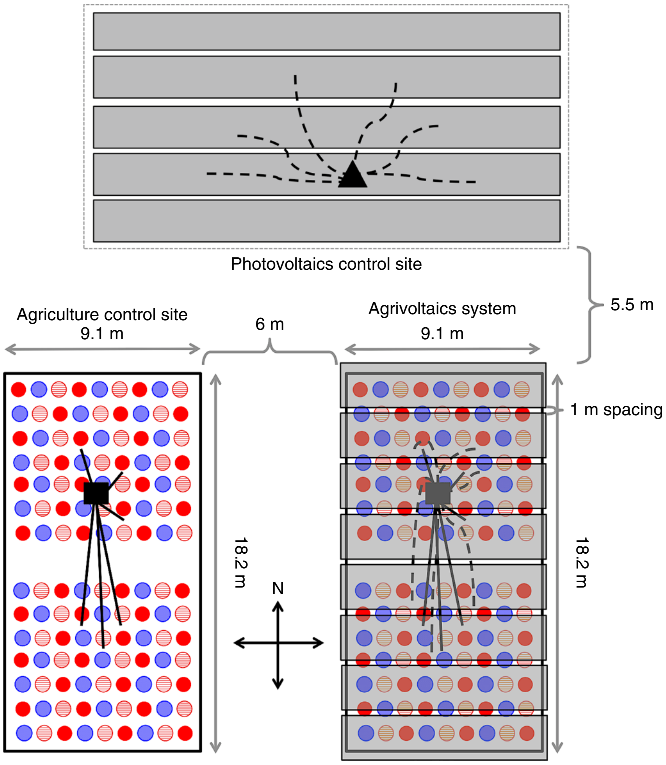

Fig. 4 | Map of the experimental area, which consisted of an agricultural control site, a traditional ground-mounted PV installation and an agrivoltaic system site. The solid red, blue and hashed circles represent tomato, jalapeño and chiltepin plants, respectively. The black square represents the location of the meteorologicalmeasurement station, and the solid lines extending from the square represent the locations of the soil moisture sensors. The dashed lines extending from the square represent the locations of the thermistors adhered to the PV panels for temperature measurement.

that remained in the soil after each irrigation event in a traditional, or control, growing area versus under an agrivoltaic system (Fig. 4). We detected the greatest influence of the agrivoltaic system on soil moisture savings when we irrigated every 2 d, as soil moisture remained ~15% greater (3.2% volumetric units) than in the control setting (Fig. 5a,c) before the subsequent irrigation event. Nevertheless, even with daily irrigation the agrivoltaic system remained 5% greater (1.0% volumetric units) before the subsequent irrigation event than in the control setting (Fig. 5b,d). Importantly, soil moisture levels in the agrivoltaic setting after 2 d remained above the driest points seen in the control setting after daily irrigation events, suggesting that even more reduced irrigation in an agrivoltaic system may be possible. The potential reduction in water use within agrivoltaics could be substantial and warrants further research in future studies, especially given the uncertainties in projected future rainfall and water allocations.

Potential impacts for improved renewable energy production. Given the inherent sensitivity of PV panels to temperature, any cooling of panels below current daytime temperatures >30 °C will positively impact its efficiency[46,47]. We found that PV panels in a traditional ground-mounted array were significantly warmer during the day and experienced greater within-day variation than those over an agrivoltaic understorey (Fig. 6a). We attribute these lower daytime temperatures in PV panels in the agrivoltaic system (Fig. 6b) to the greater balance of latent heat energy exchange from plant transpiration relative to sensible heat exchange from radiation from bare soil (the typical installation method). Across the core growing season, PV panels in an agrivoltaic system were ~8.9 + 0.2 °C cooler in daylight hours. This reduction in temperature can lead to an increase in system performance. Using the system advisor model (SAM) for a traditional and a colocation PV system in Tucson, AZ, we calculated that temperature reductions documented here in the growing months of May–July from the colocation system led to a 3% increase in generation over those months, and a 1% increase in generation annually.

Discussion

Together, these results suggest that the novel colocation of agriculture and PV arrays could have synergistic effects that support the production of ecosystem services such as crop production, local climate regulation, water conservation and renewable energy production. Our results suggest that an agrivoltaic colocation design not only mitigates energy balance challenges associated with the

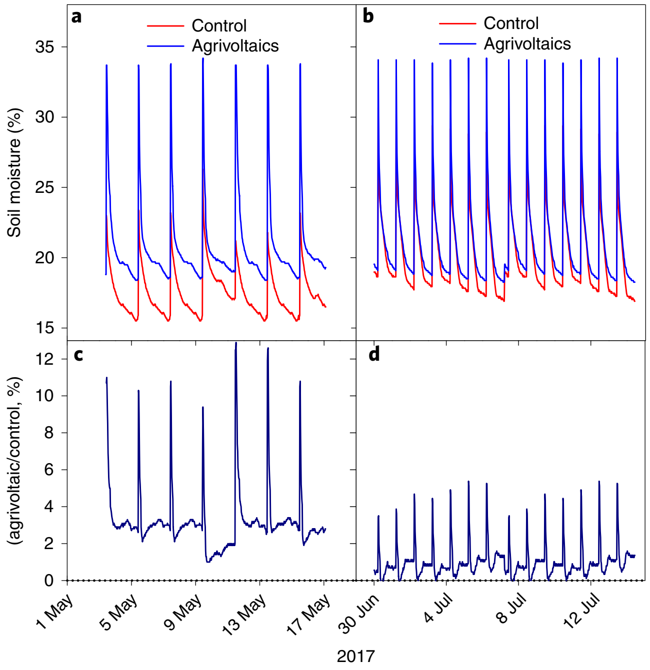

Fig. 5 | Impacts of colocation of agriculture and solar PV panels (agrivoltaic) over traditional (control) installations on irrigation resources, as indicated by soil moisture. a,**b**, Thirty-minute average volumetric water content (soil moisture) in the top 5 cm of the soil in the agrivoltaic and control settings. **c**,**d**, Differences between soil moisture in an agrivoltaic setting and in control plots, where positive values indicate additional moisture in the agrivoltaic setting. **a**,**c**, A period when plots were watered every two days. **b**,**d**, A period when plots were watered every day.

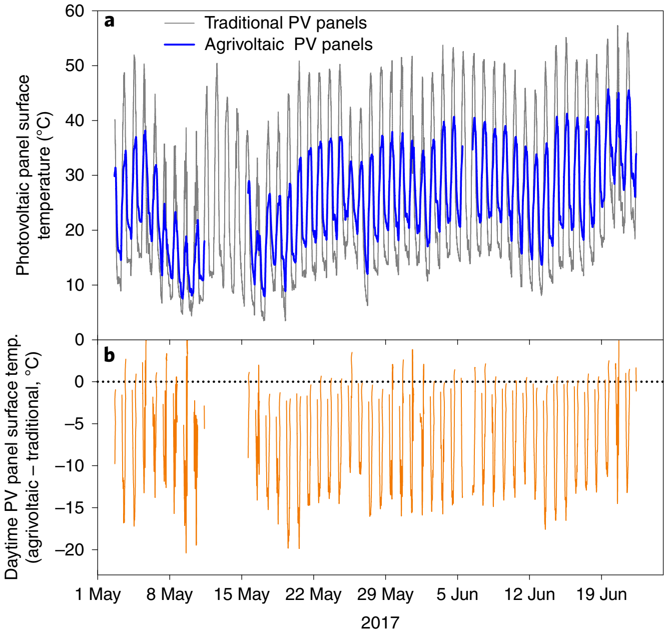

Fig. 6 | Impacts of colocation of agriculture and solar PV panels (agrivoltaic) over traditional ground-mounted installations on the surface temperature of PV panels. a, Thirty-minute average photovoltaic panel temperature, as measured by a thermistor placed on the rear of panels. **b**, Differences in panel temperature between the agrivoltaic and traditional ground-mounted settings. Negative values indicate the degree to which panels in the agrivoltaic setting were cooler. Positive values—indicating warmer conditions—occurred during the night-time when the PV systems were not operating.

development of a PV site, but also increases the collective ecosystem services associated with an area[2]. We should no longer follow the narrow understanding of land use that has averred a zero-sum-game of competition between renewable energy and agricultural food production. In fact, we have shown that each portion of the food–energy–water nexus can respond positively to the colocation of these seemingly disparate needs. In this novel ecosystem, plants growing in an agrivoltaic setting (under PV) receive less light, but this has now been shown to be associated with positive trade-offs in terms of reduced evaporative loss of soil moisture in a dryland area. The efficacy and extent of positive effect was dependent on the plant species. Growing food crops in an agrivoltaic system led to increased CO_2 uptake and fruit production in two of three species, and the one species that did not exhibit higher production achieved equal production with only about 35% of the transpirational water loss. At the same time, that transpirational water loss also created an energy balance shifted more towards latent heat exchange and less sensible heat flux to the atmosphere in the move from traditional agriculture to an agrivoltaic system. This resulted in the PV panels in an agrivoltaic setting being significantly cooler in the daytime—a positive trade-off for shading a vegetative understorey, which should lead to increased renewable energy production—and longer retention times of irrigation waters within the soil.

Additional species should be explored to capture a wider understanding of which plant functional types are most appropriate for this new type of food production; additional solar infrastructure designs and configurations should be considered, to better understand trade-offs in energy output and plant productivity; and additional installations around a biogeographic gradient should be explored to quantify the relative impacts, as have been documented here. It is possible that alternative solar configuration, crop and location combinations could lead to disadvantageous outcomes, such as excess soil moisture, crop yield reductions or increased risks to solar infrastructure. Future field sites could explore these variations and thereby contribute to a more comprehensive understanding of agrivoltaics opportunities. Hitherto uninvestigated for agrivoltaics are the potential for the restoration of endemic plant communities to provide increases in solar panel efficiencies, the retrofitting potential of the groundcover of existing solar facilities to accommodate food crops or endemic plant communities, and how pollinator habitat planted underneath arrays could benefit local agriculture. Also unexplored are issues tied to the physical and social impacts of farm labourers working in an agrivoltaic system. To date we have found no ill effects, and future studies could quantify these impacts through the metric of human thermal comfort (HTC)[72], which takes into account not only air temperature but also sun exposure. Given the milder microclimate under PV panels within an agrivoltaic system, we hypothesize that HTC would be greater than in a control system, and this could be particularly important in dryland environments where rates of heat stroke and heat-related death among farm workers are especially high. Economically, this novel microclimate may also extend growing seasons and protect against untimely frosts. The land-leasing opportunity may additionally provide revenue to farmers to ward off development pressures and keep food costs down. All of these impacts—water scarcity, environmental sensitivity of our food crops, the efficiency of PV panels and the HTC of the people that bring food to market—are especially vulnerable to projected climate change patterns and extremes.

This study represents the first experimental and empirical examination of the potential for an agrivoltaic system to positively impact each component of the food–energy–water nexus. Our results from a dryland system indicate a reduction in daytime temperatures of the solar panels (energy) and microclimate under the panels (food), and a dampening in the diurnal fluctuations of each and day-to-day fluctuations in soil moisture in irrigated agriculture (water). Together, our findings suggest that a dryland agrivoltaic system may be a resilient energy and food system that has reduced vulnerabilities to future climate variability. However, there are probable barriers to wider adoption, which include challenges associated with some forms of mechanized farming and harvest and the additional costs associated with elevating PV arrays to allow for food production in the understorey. An integrated approach to the physical and social dimensions of our food and energy systems is key in supporting decision making regarding PV development and sustainable food and energy production in a changing world. The results presented here provide a foundation, direction and motivation for future explorations towards resilience of food and energy systems in the future.

Methods

Site description. We established the Biosphere 2 Agrivoltaics Learning Lab in August 2016. The site is operated by the University of Arizona, and is situated on the ground of the Biosphere 2 research centre north of Tucson, AZ, USA (32.578989 °N, 110.851103 °W, elevation 1,381 m above sea level). The climate in Tucson is hot desert (Koppen classification BWh), which experiences a mean annual temperature of 21.6 °C and is characterized as having bimodal precipitation with a summer monsoon and winter rains. Average precipitation is limited to <30 cm, but the magnitude and timing of storms have increasingly varied in recent decades[73]. Summers are hot, with air temperature regularly averaging 38 °C and soil surface temperatures exceeding 45 °C. Winter temperatures are moderate, with occasional light frosts in January. Summer season agriculture in this region is primarily a mix of vegetables, with tomato, pepper, herbs, eggplant and melon being most prominent.

The site involves replicated rows of agricultural crop species growing in either traditional, open-sun growing conditions or under a raised solar PV panel array (agrivoltaics; Fig. 4). Each of these areas is approximately 9.1 × 18.2 m^2. The fixed panels within the agrivoltaic system are 3.3 m above the soil surface at their lowest point, whereas they are only about 0.3–1.0 m above the ground in the traditional PV configuration. All panels face south, at a latitude angle of 32°[48]. There is 1 m of spacing between each row of PV panels.

Both sites were excavated down to a depth of approximately 25.5 cm, and the native soil was replaced and amended with an organic 'Garden Blend', which is a mixture of 75% organic compost and 25% sandy soil (Tank's Green Stuff). An irrigation system was established that delivered equal amounts—in terms of rate and cumulative application—across the control and agrivoltaics plots. Equality in irrigation delivery was confirmed on two occasions by collecting drip water and measuring total volumes at random emitters across the plots. We planted 42 replicate plants of each of three agricultural species from the same family (Solanaceae) that represent different adaptive niches for dryland environments: *C. annuum* var. *glabriusculum*, *C. annuum* var. *annuum* and *S. lycopersicum* var. *cerasiforme*; Fig. 4). All of the replicate individuals originated from the same seed source—a homogenized collection of seeds from fruits produced by the previous year's growth. Seeds were planted within a matrix of the same 'Garden Blend' in February 2017 in a greenhouse, and were then transplanted to the research site in March 2017. We were cognisant of the potential for inducing error by studying plants along the border of our treatment due to 'edge effects'[74]. We avoided this issue by selecting plants that were at least three rows in from any edge of the experimental array.

For most of the experiment, irrigation was delivered daily at a rate of 3.79 l min^{-1} for 30 min by a multi-valve irrigation system (Rain Bird ESP-Modular Controller), but in May 2017 we reduced irrigation to an alternate-day schedule to quantify rates of water use under this water-saving schedule. Irrigation was supplied through standard 1.27-cm polyethylene drip irrigation tubing. We conducted calibrations on the uniformity of the irrigation system's delivery twice per year. To confirm that the irrigation emitters were delivering equal amounts of water despite variable distances from the irrigation control box, we used graduated cylinders to calculate rates in terms of volumes per minute. We maintained these measurement installations for one full growing season, to capture variation due to sun angle and extremes associated with hot and cold periods at the edge of the growing season.

At the end of the growing season in August 2017, we harvested all of the fruits for each of the ten replicate study plants per species. In so doing, we captured the productivity of each plant in terms of marketable produce. We present here the production per individual, to underscore the impacts of a changing microclimate due to the agrivoltaics system approach on productivity at an organismal level.

Monitoring equipment and variables monitored. Ambient air temperature (°C) and relative humidity (%) were measured with a shaded, aspirated temperature probe 2.5 m above the soil surface (Vaisala HMP60). Importantly, the temperature probes used within the agrivoltaic and control settings were cross-validated for precision (closeness of temperature readings across all probes) at the onset of the experiment. We also monitored incoming PAR (LI-190R, LI-COR) at 2.5 m above the soil surface. Both of these probes were mounted on a post placed within the centre of each installation, to avoid any variance due to edge effects around each plot. We monitored volumetric water content and soil temperature at 5-cm depth (ECH$_2$O 5TM, METER Group) at six points across each of the control and agrivoltaic system sites (Fig. 4). Data across the six points were averaged to give a single representative value for each time period for each site.

Finally, we monitored solar panel temperatures using precision integrated-circuit temperature sensors (LM35CA thermistor, Texas Instruments) adhered to the rear of each of six different solar panels[75]. To compare the temperatures of panels in the agrivoltaic setting to traditional ground-mounted solar panels, we replicated this measurement scheme on six panels within a solar array approximately 10 m away in the same research area of Biosphere 2 (Fig. 4). All of these measurements were recorded at 30-min intervals throughout a 24-h day, and data were recorded on a data-logger (CR1000, Campbell Scientific). We calculated averages of daytime PV panel temperatures using all data from daylight hours, when PAR was >10 μmol m^{-2} s^{-1}. We used SAM parameterized for Tucson, AZ, USA to quantify normal power generation for an example 200 kW DC system[76,77]. For this simulation, we used standard SAM defaults for a PV array of SunPower-X21-335 (mono-crystalline Silicon) modules with a nominal efficiency of 20.5521%. The only variable that differed between the adjacent traditional and agrivoltaic installations was PV panel temperature. A traditional PV installation would generate 373 MWh per year (21.4% capacity factor), whereas the agrivoltaic installation, with the reduced temperatures shown here, would generate 377 MWh per year (21.6% capacity factor). This equates to an increase of approximately 1% per year in annual generation based on only these three months of documented cooling.

Leaf-level measurements of CO$_2$ and water exchange. Measurements of leaf-level net photosynthesis (A_{net}) and transpiration were conducted using a LI-6400 portable photosynthesis system (LI-COR)[78–81,82]. A red–blue light source (LI-6400-02b) attached to the leaf cuvette provided constant irradiance of ambient light levels for each measurement area (open sun versus shade under the PV panels). The cuvette (CO$_2$) was held constant at 400 ppm across all measurements. Cuvette air temperature was set to match that of ambient conditions at each measurement time point. Hourly measurements were conducted between 05:00 and 21:00 mean solar time—for a total of 17 measurement periods—to capture the full daily carbon assimilation and water loss period. Once chamber conditions and gas-exchange rates of A_{net} had stabilized, the two infrared gas analysers within the instrument were matched, and gas-exchange data were logged five times across a 1-min period and averaged. For each of the treatments (control and agrivoltaics), we measured five replicates of each of the three plant types—for a total of 30 individuals. We conducted these measurements over the course of a 5-d period in the middle of the growing season, to capture instantaneous rates of leaf-level gas exchange and to gain insight into plant performance. All leaves that were within the 2 × 3-cm cuvette for gas-exchange measurements were harvested after measurements and stored in paper envelopes in a chilled cooler for transport to the laboratory, so that we could correct our measurements on a per-unit leaf area basis. We obtained wet leaf mass, and then sampled leaf area was determined using an LI-3100C area meter (LI-COR). Samples were then air-dried to obtain dry leaf mass.

These measurements of CO$_2$ assimilation and water loss were used to infer daily cumulative by first taking the instantaneous measures, which have units of μmol m^{-2} s^{-1}, and up-scaling these to the hourly estimates. We then accumulated these hourly values for the entire daytime period.

Throughout this procedure, we captured the productivity of each plant in terms of carbon uptake at the leaf scale.

Statistical analysis. Comparisons of cumulative CO$_2$ uptake, daily water use efficiency (WUE; daily CO$_2$ uptake/daily transpirational water loss) and fruit production between the control and agrivoltaic treatment were made using Tukey's honestly significant difference (HSD) test. Standard errors to calculate HSD were made using pooled values at either the daily (CO$_2$ uptake and WUE) or growing season (fruit production) scale. We used midnight and noon values to examine maximum and minimum, respectively, differences in PV panel temperatures between the agrivoltaic and traditional ground-mounted settings. Comparisons among the sites were made using the same Tukey's HSD test.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from the corresponding author on request.

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References

1. Beckman, J. & Xiarchos, I. M. Why are Californian farmers adopting more (and larger) renewable energy operations? *Renew. Energy* **55**, 322–330 (2013).
2. Hernandez, R. R. et al. Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.* **29**, 766–779 (2014).
3. Hernandez, R. R., Hoffacker, M. K. & Field, C. B. Land-use efficiency of big solar. *Environ. Sci. Technol.* **48**, 1315–1323 (2014).
4. *Renewables 2014 Global Status Report* (REN21 Secretariat, 2014).
5. Hoffacker, M. K., Allen, M. F. & Hernandez, R. R. Land-sparing opportunities for solar energy development in agricultural landscapes: a case study of the great Central Valley, CA, United States. *Environ. Sci. Technol.* **51**, 14472–14482 (2017).
6. Trainor, A. M., McDonald, R. I. & Fargione, J. Energy sprawl is the largest driver of land use change in United States. *PLoS ONE* **11**, 7896–7906 (2016).
7. Bazilian, M. et al. Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* **39**, 7896–7906 (2011).
8. Albrecht, T. R., Crootof, A. & Scott, C. A. The water-energy-food nexus: a systematic review of methods for nexus assessment. *Environ. Res. Lett.* **13**, 043002 (2018).
9. Harwood, S. A. In search of a (WEF) nexus approach. *Environ. Sci. Policy* **83**, 79–85 (2018).
10. Biggs, E. M. et al. Sustainable development and the water-energy-food nexus: a perspective on livelihoods. *Environ. Sci. Policy* **54**, 389–397 (2015).
11. Bogardi, J. J. et al. Water security for a planet under pressure: interconnected challenges of a changing world call for sustainable solutions. *Curr. Opin. Environ. Sustain.* **4**, 35–43 (2012).
12. Dupraz, C. et al. Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. *Renew. Energy* **36**, 2725–2732 (2011).
13. Jaeger, W. K. et al. Finding water scarcity amid abundance using human-natural system models. *Proc. Natl Acad. Sci. USA* **114**, 11884–11889 (2017).
14. Lobell, D. B., Schlenker, W. & Costa-Roberts, J. Climate trends and global crop production since 1980. *Science* **333**, 616–620 (2011).
15. Elliott, J. et al. Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proc. Natl Acad. Sci. USA* **111**, 3239–3244 (2014).
16. Liu, J. et al. Achieving sustainable irrigation water withdrawals: global impacts on food security and land use. *Environ. Res. Lett.* **12**, 104009 (2017).
17. Bradford, J. B. et al. Future soil moisture and temperature extremes imply expanding suitability for rainfed agriculture in temperate drylands. *Sci. Rep.* **7**, 12923 (2017).
18. Kasler, D. More California farmland could vanish as water shortages loom beyond drought. *The Sacramento Bee* (26 November 2015).
19. Waha, K. et al. Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups. *Reg. Environ. Change* **17**, 1623–1638 (2017).
20. Reyer, C. P. O. et al. Climate change impacts in Latin America and the Caribbean and their implications for development. *Reg. Environ. Change* **17**, 1601–1621 (2017).
21. Tumbo, S. D. et al. Impact of projected climate change on agricultural production in semi-arid areas of Tanzania: a case of same district. *Afr. Crop Sci. J.* **20**, 453–463 (2012).
22. Adhikari Umesh, N., Pouyan, A. & Woznicki, S. A. Climate change and eastern Africa: a review of impact on major crops. *Food Energy Secur.* **4**, 110–132 (2015).
23. Knox, J., Hess, T., Daccache, A. & Wheeler, T. Climate change impacts on crop productivity in Africa and South Asia. *Environ. Res. Lett.* **7**, 034032 (2012).
24. Schlenker, W. & Lobell, D. B. Robust negative impacts of climate change on African agriculture. *Environ. Res. Lett.* **5**, 014010 (2010).
25. Jiménez Cisneros, B. E. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) Ch. 3, 229–269 (IPCC, Cambridge Univ. Press, 2014).
26. Bevan, G. Renewable energy and climate change. *Significance* **9**, 8–12 (2012).
27. Jaglom, W. S. et al. Assessment of projected temperature impacts from climate change on the U.S. electric power sector using the Integrated Planning Model. *Energy Policy* **73**, 524–539 (2014).
28. Gonzalez-Diaz, A. et al. Effect of the ambient conditions on gas turbine combined cycle power plants with post-combustion CO_2 capture. *Energy* **134**, 221–233 (2017).
29. Hamlet, A. F., Lee, S.-Y., Mickelson, K. E. B. & Elsner, M. M. Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. *Clim. Change* **102**, 103–128 (2010).
30. Turner, S. W. D., Ng, J. Y. & Galelli, S. Examining global electricity supply vulnerability to climate change using a high-fidelity hydropower dam model. *Sci. Total Environ.* **590**, 663–675 (2017).
31. Madani, K. & Lund, J. R. Estimated impacts of climate warming on California's high-elevation hydropower. *Clim. Change* **102**, 521–538 (2010).
32. *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather* (United States Department of Energy, 2013).
33. Rogers, J. et al. *Water-Smart Power: Strengthening the U.S. Electricity System in a Warming World* (2013).
34. Macknick, J. et al. *Water and Climate Impacts on Power System Operations: The Importance of Cooling Systems and Demand Response Measures* (2016).
35. van Vliet, M. T. H., Wiberg, D., Leduc, S. & Riahi, K. Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nat. Clim. Change* **6**, 375–380 (2016).
36. van Vliet, M. T. H. et al. Vulnerability of US and European electricity supply to climate change. *Nat. Clim. Change* **2**, 676–681 (2012).
37. Liu, L., Hejazi, M., Li, H., Forman, B. & Zhang, X. Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations. *Nat. Energy* **2**, 17109 (2017).
38. Miara, A. et al. Climate and water resource change impacts and adaptation potential for US power supply. *Nat. Clim. Change* **7**, 793–798 (2017).
39. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (IPCC Working Group III, Cambridge Univ. Press, 2011).
40. US Energy Information Administration *June 2016 Monthly Energy Review U.S. Department of Energy* (Office of Energy Statistics, 2016).
41. Bazilian, M. et al. Re-considering the economics of photovoltaic power. *Renew. Energy* **53**, 329–338 (2013).
42. *SunShot Vision Study, DOE/GO-102012-3037* (US Department of Energy, 2012).
43. Hartmann, H. M. et al. *Understanding Emerging Impacts and Requirements Related to Utility-scale Solar Development* (US Department of Energy, 2016).
44. Roberts, B. J. *Solar Production Potential across the United States* (Department of Energy, National Renewable Energy Laboratory, 2012).
45. Brown, P. & Whitney, G. *U.S. Renewable Electricity Generation: Resources and Challenges* (Congressional Research Service, 2011).
46. Kaldellis, J. K., Kapsali, M. & Kavadias, K. A. Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece. *Renew. Energy* **66**, 612–624 (2014).
47. Said, S. A. M., Hassan, G., Walwil, H. M. & Al-Aqeeli, N. The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies. *Renew. Sustain. Energy Rev.* **82**, 743–760 (2018).
48. Cronin, A. et al. Measuring degradation rates of PV systems without irradiance data. *Prog. Photovolt.* **22**, 851–862 (2014).
49. Barron-Gafford, G. A. et al. The solar heat island effect: larger solar power plants increase local temperatures. *Sci. Rep.* **6**, 35070 (2016).
50. Solecki, W. D. et al. Mitigation of the heat island effect in urban New Jersey. *Environ. Hazards* **6**, 39–49 (2005).
51. Campbell, G. S. & Norman, J. M. *An Introduction to Environmental Biophysics* 2nd edn (Springer, 1998).
52. Breshears, D. D. The grassland-forest continuum: trends in ecosystem properties for woody plant mosaics? *Front. Ecol. Environ.* **4**, 96–104 (2006).
53. Hobbs, R. J. et al. Novel ecosystems: theoretical and management aspects of the new ecological world order. *Glob. Ecol. Biogeogr.* **15**, 1–7 (2006).
54. Hobbs, R. J., Higgs, E. & Harris, J. A. Novel ecosystems: implications for conservation and restoration. *Trends Ecol. Evol.* **24**, 599–605 (2009).
55. Standish, R., Hobbs, R. J. & Miller, J. Improving city life: options for ecological restoration in urban landscapes and how these influence interactions between humans and nature. *Landsc. Ecol.* **28**, 1213–1221 (2012).
56. Nabhan, G. P. Our Coming Food Crisis. *New York Times* http://www.nytimes.com/2013/07/22/opinion/our-coming-food-crisis.html (21 July 2013).
57. Nabhan, G. P. *Growing Food in a Hotter, Drier Land: Lessons from Desert Farmers on Adapting to Climate Uncertainty* (Chelsea Green Publishing, 2013).
58. Ravi, S. et al. Colocation opportunities for large solar infrastructures and agriculture in drylands. *Appl. Energy* **165**, 383–392 (2016).
59. Amaducci, S., Yin, X. & Colauzzi, M. Agrivoltaic systems to optimise land use for electric energy production. *Appl. Energy* **220**, 545–561 (2018).
60. Aroca-Delgado, R., Perez-Alonso, J., Jesus Callejon-Ferre, A. & Velazquez-Marti, B. Compatibility between crops and solar panels: an overview from shading systems. *Sustainability* **10**, 743 (2018).
61. Valle, B. et al. Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Appl. Energy* **206**, 1495–1507 (2017).
62. Macknick, J., Beatty, B. & Hill, G. *Overview of Opportunities for Co-Location of Solar Energy Technologies and Vegetation* (National Renewable Energy Laboratory, 2013).
63. Majumdar, D. & Pasqualetti, M. J. Dual use of agricultural land: introducing 'agrivoltaics' in Phoenix Metropolitan Statistical Area, USA. *Landsc. Urban Plan.* **170**, 150–168 (2018).

64. Dinesh, H. & Pearce, J. M. The potential of agrivoltaic systems. *Renew. Sustain. Energy Rev.* **54**, 299–308 (2016).
65. Goetzberger, A. & Zastrow, A. On the coexistence of solar-energy conversion and plant cultivation. *Int. J. Sol. Energy* **1**, 55–69 (1982).
66. Marrou, H., Wery, J., Dufour, L. & Dupraz, C. Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *Eur. J. Agron.* **44**, 54–66 (2013).
67. Adeh, E. H., Selker, J. S. & Higgins, C. W. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS ONE* **13**, e0203256 (2018).
68. Marrou, H., Dufour, L. & Wery, J. How does a shelter of solar panels influence water flows in a soil-crop system? *Eur. J. Agron.* **50**, 38–51 (2013).
69. Marrou, H., Guilioni, L., Dufour, L., Dupraz, C. & Wery, J. Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? *Agric. For. Meteorol.* **177**, 117–132 (2013).
70. López-España, R. G. et al. Geographical differentiation of wild pepper (*Capsicum annuum* L. var. *glabriusculum*) populations from northwestern Mexico. *Phyton* **85**, 131–141 (2016).
71. Bosland, P. & Votava, E. *Peppers: Vegetable and Spice Capsicums* (CABI Publishing, 2000).
72. Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M. & Demuzere, M. Watering our cities: the capacity for water sensitive urban design to support urban cooling and improve human thermal comfort in the Australian context. *Prog. Phys. Geogr.* **37**, 2–28 (2013).
73. Luong, T. M. et al. The more extreme nature of North American monsoon precipitation in the Southwestern United States as revealed by a historical climatology of simulated severe weather events. *J. Appl. Meteorol. Climatol.* **56**, 2509–2529 (2017).
74. Schmidt, M., Jochheim, H., Kersebaum, K.-C., Lischeid, G. & Nendel, C. Gradients of microclimate, carbon and nitrogen in transition zones of fragmented landscapes—a review. *Agric. For. Meteorol.* **232**, 659–671 (2017).
75. Martinez, M. A., Andujar, J. M. & Enrique, J. M. Temperature measurement in PV facilities on a per-panel scale. *Sensors* **14**, 13308–13323 (2014).
76. Blair, N. et al. *System Advisor Model (SAM) General Description (Version 2017.9.5)* (National Renewable Energy Laboratory, 2018).
77. Blair, N. et al. *System Advisor Model, SAM 2014.1.14: General Description* (National Renewable Energy Laboratory, 2014).
78. Barron-Gafford, G. A. et al. Impacts of hydraulic redistribution on grass-tree competition vs facilitation in a semi-arid savanna. *New Phytol.* **215**, 1451–1461 (2017).
79. Hamerlynck, E. P., Scott, R. L. & Barron-Gafford, G. A. Consequences of cool-season drought-induced plant mortality to Chihuahuan Desert grassland ecosystem and soil respiration dynamics. *Ecosystems* **16**, 1178–1191 (2013).
80. von Caemmerer, S. & Farquhar, G. D. Some relationships between the biochemistry of photosynthesis and the gas exchange of leaves. *Planta* **153**, 376–387 (1981).
81. Barron-Gafford, G. A. et al. Photosynthetic temperature responses of co-occurring desert winter annuals with contrasting resource-use efficiencies and different temporal patterns of resource utilization may allow for species coexistence. *J. Arid Environ.* **91**, 95–103 (2013).
82. Barron-Gafford, G. A., Scott, R. L., Jenerette, G. D., Hamerlynck, E. P. & Huxman, T. E. Temperature and precipitation controls over leaf- and ecosystem-level CO_2 flux along a woody plant encroachment gradient. *Glob. Change Biol.* **18**, 1389–1400 (2012).

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Author contributions

G.A.B.-G., R.L.M., L.F.S., I.B.-M., D.T.B. and M.T. established research sites and installed monitoring equipment. G.A.B.-G. directed research. R.L.M., L.F.S., I.B.-M., D.T.B. and M.T. conducted most of the site maintenance. G.A.B.-G., M.A.P.-Z., G.P.N. and J.E.M. led efforts to secure funding for the research. All authors discussed the results and contributed to the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No custom code was used for data collection.
Data analysis	We used the program Statistix (v. 8.0) Analytical Software, Tallahassee, FL, USA

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The site involves replicated rows of agricultural crop species growing in either (i) traditional, open sun growing conditions or (ii) under a raised solar photovoltaic panel array (agrivoltaics). occasions by collecting drip water and measuring total volumes at random emitters across the plots. We planted 42 replicate plants of each of three agricultural species from the same family (Solanaceae) that represent different adaptive niches for dryland environments: (i) chiltepin pepper (Capsicum annuum var. glabriusculum), (ii) jalapeño (Capsicum annuum var. annuum), and (iii) cherry tomato (Solanum lycopersicum var. cerasiforme)
Research sample	We established the Biosphere 2 Agrivoltaics Learning Lab in August 2016. The site is operated by the University of Arizona, and is situated on the ground of the Biosphere 2 research center north of Tucson, Arizona, USA (32.578989°N, 110.851103°W; elevation: 1381 m ASL). We planted 42 replicate plants of each of three agricultural species from the same family (Solanaceae) that represent different adaptive niches for dryland environments: (i) chiltepin pepper (Capsicum annuum var. glabriusculum), (ii) jalapeño (Capsicum annuum var. annuum), and (iii) cherry tomato (Solanum lycopersicum var. cerasiforme). All of the replicate individuals originated from the same seed source – a homogenized collection of seeds from fruits produced by the previous year's growth. Seeds were planted within a matrix of the same 'Garden Blend' in February 2017 in a greenhouse, and then they were transplanted to the research site in March 2017. We were cognizant of the potential for inducing error by studying plants along the border of our treatment due to "edge effects" 74. We avoided this issue by selecting plants that were at least three rows in from any edge of the experimental array.
Sampling strategy	In previous studies, we conducted trials with various numbers of replicates to statistically determine that having five targeted plants per measurement period was an adequate amount.
Data collection	Measurements of leaf-level net photosynthesis (Anet) and transpiration were conducted using a LI-6400 portable photosynthesis system (LI-COR, Lincoln, NE, USA). For each of the treatments (control and agrivoltaics), we measured five replicates of each of the three plant type – for a total of 30 individuals. We conducted these measurements over the course of a five-day period in the middle of the growing season to capture instantaneous rates of leaf-level gas exchange and gain insight into plant performance.
Timing and spatial scale	We conducted plant-based measurements over the course of a five-day period in the middle of the growing season to capture instantaneous rates of leaf-level gas exchange and gain insight into plant performance. The study was run for an entire growing season, and meteorological data reflect this time period.
Data exclusions	No data were excluded from this study.
Reproducibility	We have ensured reproducibility by using very regular plant spacings and locations within a planted scheme, documented irrigation delivery rates and confirmed those delivery rates using graduate cylinders.
Randomization	Plant replicates were chosen based on a predetermined location map to avoid human bias in plant selection.
Blinding	Blinding was achieved by giving a unique number to all replicates.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	The climate in field site is a hot desert (Koppen Bwh) that experiences a mean annual temperature of 21.6 °C and is characterized as having bimodal precipitation with a summer monsoon and winter rains. Average precipitation is limited to less than 30 cm. Summers are hot, with air temperature regularly averaging 38°C and soil surface temperatures exceeding 45 °C. Winter temperatures are moderate, with occasional light frosts in January.
Location	The site is situated on the ground of the Biosphere 2 research center north of Tucson, Arizona, USA (32.578989°N, 110.851103° W; elevation: 1381 m ASL).
Access and import/export	No import / export permits were required for this project.
Disturbance	No disturbance was created by this experiment.

Reporting for specific materials, systems and methods

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☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging