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OPINION

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How to reconcile renewable energy and agricultural production in a drying world

Andreas H. Schweiger | Lisa Pataczek

Institute of Landscape and Plant Ecology, Department of Plant Ecology, University of Hohenheim, Ottilie-Zeller-Weg 2, 70599 Stuttgart, Germany

Correspondence
Andreas H. Schweiger, Institute of Landscape and Plant Ecology, Department of Plant Ecology, University of Hohenheim, Ottilie-Zeller-Weg 2, 70599 Stuttgart, Germany.
Email: andreas.schweiger@uni-hohenheim.de

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Societal Impact Statement

Renewable energies such as photovoltaics can mitigate climate change by replacing fossil fuels, but they will compete with other forms of land use when implemented in open space. Agrivoltaics provide a promising approach to reconciling food and energy needs by allowing for agricultural and electrical power production on the same area of land. Agrivoltaics have a high potential to attenuate negative effects of drought on crop growth and, thus, can help to increase resilience of agricultural production under increasingly variable environmental conditions. This drought attenuation potential will be especially relevant for regions where drought and population growth co-occur.

Summary

Water scarcity is threatening food security and other, plant-related ecosystem services. Renewable energy production provides a sustainable strategy to replace fossil fuel and, by this, mitigate climate change. However, common forms of renewable energy production such as photovoltaics in open space directly compete with agriculture. Agrivoltaics are proposed as a promising technology to reconcile food and energy needs by allowing for agricultural and electrical power production on the same area of land. However, general understanding of the potential of agrivoltaics to facilitate crop yield under changing climatic conditions is lacking. In this study we provide an overview on the effects of agrivoltaics on microclimate and crop growth and yields. We furthermore quantify the global potential of agrivoltaics to attenuate drought effects on crops and develop a conceptual framework for evaluating interactions between solar power and agricultural production under changing climatic conditions. Generally, shading by agrivoltaics will reduce yield in comparison to maximum possible yield under unshaded, well-watered conditions but can reduce interannual variation in yields caused by drought, thus, increase resilience of agricultural production. This drought attenuation potential of agrivoltaics seems to be especially promising in the drought prone regions of the world. Land use efficiency of agrivoltaic systems is directly linked the degree of crop shading which covaries with the drought attenuation potential but will ultimately be guided by political decisions on how to weight energy production vs. food security. The latter depends on economic, societal and ecological aspects related to the implementation of agrivoltaics.

KEYWORDS
climate change, drought, drought mitigation, dual land use, food security, land sharing, resilient agriculture

1 | INTRODUCTION

Climate change is globally affecting energy and resource availability for plants with rising temperatures and changes in the amount and temporal distribution of precipitation being the main symptoms (IPCC, 2021). Water availability is drastically declining in many regions of the world due to a strong drop in precipitation amount and high rates of evaporative water demand (Greve et al., 2014; Xiao et al., 2020). Consequently, plants are experiencing edaphic and atmospheric water deficits in increasing frequency and severity during their life spans (Abdalla et al., 2022). This magnifies the risk of food insecurity and loss of other, plant-related ecosystem services for a growing human population (Toulotte et al., 2022). Water scarcity is expected to further increase in many regions, including Europe, which will even aggravate food shortage and other ecosystem disservices (Böhnisch et al., 2021).

Fossil fuel consumption for energy production is one of the biggest drivers of anthropogenic climate change. At the same time, the demand for energy and food is steadily increasing due to global population growth and economic development (Allardyce et al., 2017). Renewable energy production is believed to provide a sustainable strategy to replace fossil fuel and, by this, mitigate climate change by still fulfilling a growing, global demand for energy (Adeh et al., 2018; Graebig et al., 2010; Späth, 2018). For this reason, many countries target to increase their share of renewable energy production over the next few decades (European Commission, 2010; Lilliestam et al., 2014).

Solar power, that is, the transformation of solar energy into electric energy via photovoltaics (PVs), is considered to be the most abundant source of renewable energy and is becoming, at the same time, more affordable—facts that favour the global expansion of PV (Adeh et al., 2018; AL-agele et al., 2021; Breyer et al., 2017; Muñoz-García & Hernández-Callejo, 2022). However, the installation of PV on open space directly competes with other forms of land use. With 38% of global land surface being used for agricultural production, agriculture is the most dominant form of land use globally (Allardyce et al., 2017; FAO, 2021). This seems to provoke a trade-off between a transformation in the global energy production via a large-scale implementation of PV and global food security under accelerating, global climatic changes. This is exemplified in Germany, where more than 50% of conventional ground-mounted PV were installed on previous arable land by 2018 (Böhm et al., 2022). This land-use conflict is exacerbated with increasing population size and, thus, becomes especially relevant for regions such as India or Africa where the frequency and severity of drought events and population size increase at the same time (Dinesh & Pearce, 2016; Mahto et al., 2021).

Agrivoltaic systems are proposed as a promising approach to reconcile food and energy needs by allowing for agricultural and electrical power production on the same area of land. This can be realized by either elevating PV panels to working height and cultivating crops underneath or by cultivating crops in between the PV modules, which can be stilted vertically or horizontally near to the ground (Figure 1; Amaducci et al., 2018; Feuerbacher et al., 2021; Goetzberger & Zastrow, 1981; Laub et al., 2022). Several studies published in the last years highlight the potential of agrivoltaics to simultaneously spare land resources while increasing land use efficiency (LUE) of up to 70% (Dupraz et al., 2011; Weselek et al., 2019). In these studies, LUE is frequently quantified as land equivalent ratio (LER), which represents the sum of the yield ratios of dual land use (agrivoltaic system) to mono land use (separate production of energy and food) (Dupraz et al., 2011; Trommsdorff et al., 2021).

Agrivoltaic systems have been shown to negatively affect crop growth and, thus, yield by shading (Campana et al., 2021; Gonocruz et al., 2021; Weselek, Bauerle, Hartung, et al., 2021). However, this negative effect has been reported to reverse into a facilitating effect on plant growth under drought conditions by reducing evapotranspiration (Barron-Gafford et al., 2019; Weselek, Bauerle, Hartung, et al., 2021; Figure 2). However, detailed understanding on the competitive or facilitative effects between solar power and agricultural production under changing climatic conditions is still insufficient (Adeh et al., 2018). In this study, we provide an overview on the existing knowledge on the effects of agrivoltaics on microclimate and

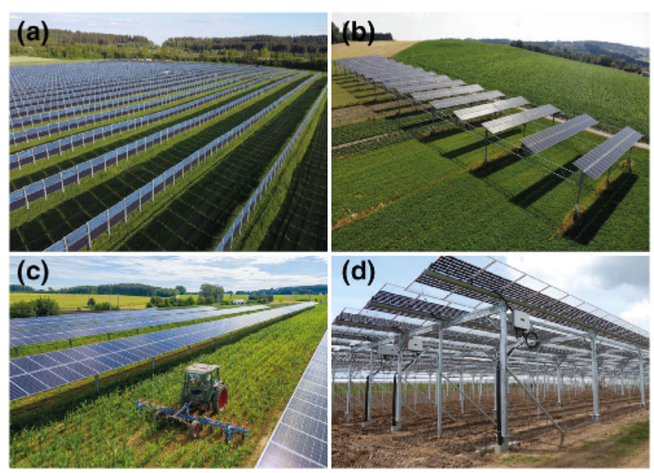

FIGURE 1 Different types of agrivoltaic systems. (a) Vertical system on grassland—farming between solar panels (Donaueschingen-Aasen, Germany, image credit: Next2Sun), (b) system with clear height on arable land—farming under solar panels (Herdwangen-Schönach, Germany, image credit: BayWa r.e.), (c) ground level system on arable land—farming between solar panels (Althegnenberg, Germany, image credit: Matthias Baumgärtner Videofotografie/ÖKO-HAUS), (d) system with clear height in orcharding—farming under solar panels (Ahrweiler, Germany, image credit: Fraunhofer ISE).

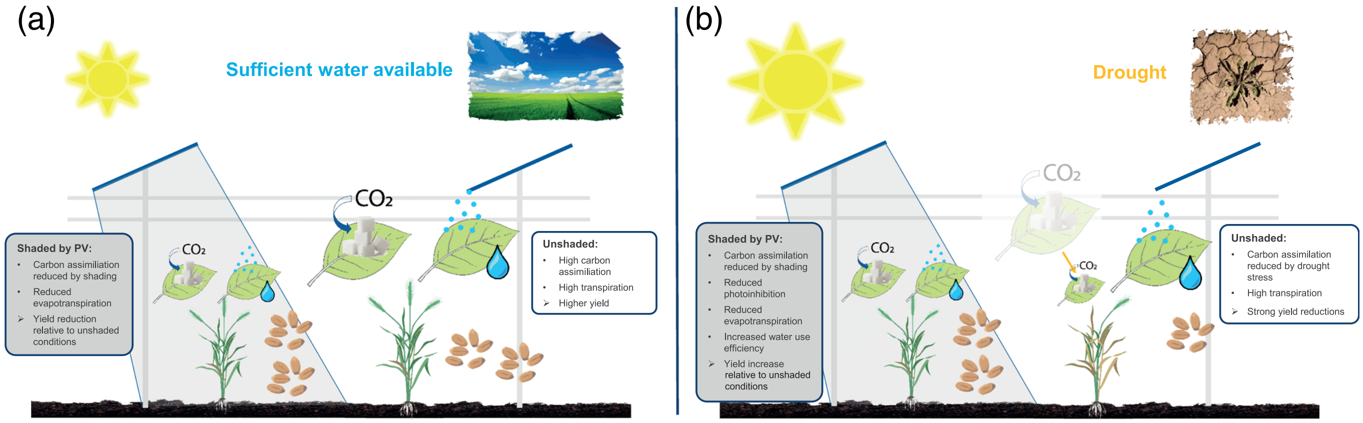

FIGURE 2 Effects of shading by photovoltaic (PV) panels on plant carbon acquisition and transpirational water loss in an agrivoltaic system. Plants shaded by PV panels will be less productive when sufficient water is available for growth in comparison to unshaded plants due to reduced photosynthetic activity (Scenario A). When water is scarce, plants will, however, profit from a reduced evaporative demand, thus, reduced transpirational water loss underneath the panels (Scenario B). Consequently, yield will be more stable under shaded conditions in comparison to unshaded conditions when interannual variation in rainfall, and thus, water availability increases.

crops and estimate the global potential of agrivoltaics to attenuate negative drought effects on crop growth, thus, agricultural production. Based on this, we develop a conceptual framework for studying interactions between solar power and agricultural production under changing climatic conditions and outline pressing research needs.

2 | THE EFFECT OF AGRIVOLTAICS ON CROPS BY MODIFYING MICROCLIMATE

2.1 | Light availability

Light is the primary source of energy for solar power generation. The same is true for plants where light is the primary energy source for photosynthetic carbon fixation, thus, crop growth. This leads to an inevitable trade-off between light used for energy production and light availability for plant growth, thus, agricultural production, when both is combined in dual land-use systems such as agrivoltaics (Apostoleris & Chiesa, 2019). Reduction of available light in agrivoltaic systems is strongly affected by panel density, ranging from 13% to 30% depending on the system design, that is, single and double density, as well as sun-tracked and static panels, the height of the modules measured from ground and the transparency rate (Amaducci et al., 2018; Toledo & Scognamiglio, 2021). Under shade, plants generally start to change carbon allocation to increase growth of aboveground, photosynthetically active tissue (Bloom et al., 1985). This response has been observed for different crops such as crisphead and cutting lettuce (*Lactuca sativa acephala*, L.), pepper (*Capsicum annuum*, L.), celeriac (*Apium graveolens subsp. rapaceum*, [Mill.] P.D. Sell), winter wheat (*Triticum aestivum*, L.) and a grass-clover mixture grown in agrivoltaic systems where plant height and/or aboveground biomass is increased under shade caused by solar panels (Marrou, Wery, et al., 2013; Weselek, Bauerle, Zikeli, et al., 2021; Zisis et al., 2019). This compensatory response might be especially relevant for crops where aboveground leaf material is of main economic interest as it is the case for lettuce. However, changes in leaf area to increase radiation interception efficiency are usually accompanied by reductions in leaf thickness, thus, increasing specific leaf area (SLA; Xu et al., 2021). These changes in SLA have been observed, for example, for lettuce and apple trees growing in agrivoltaic systems (Juillion et al., 2022; Marrou, Wery, et al., 2013; Valle et al., 2017). Increasing SLA will affect crop quality of leafy vegetables and might imply new challenges on harvest, packaging and marketing. Furthermore, species-specific differences in such kind of compensatory responses will exist among different crops. These differences will be linked to the shade tolerance of crops with responses probably being more pronounced for the more shade tolerant species (Evans & Poorter, 2001; Xu et al., 2021). However, detailed understanding of the relationships between shading and compensatory responses of different crops is lacking and needs further investigations. Nevertheless, in areas with high irradiance including high rates for harmful UV radiation, shade through PV panels can counteract photoinhibition and irreparable damage of the photosynthetic apparatus and, thus, stabilize photosynthetic carbon gain as the basis for crop productivity (Murata et al., 2007).

Furthermore, light spectrum is observed to change in agrivoltaic systems, leading to altered amounts of direct, diffuse and reflected photosynthetically active radiation (PAR) being available for plants growing underneath PV panels, with increasing ratios of diffuse to direct radiation (Armstrong et al., 2014; Ma Lu et al., 2022). Leaf-level photosynthesis in sun leaves of C_3 and C_4 plants has been demonstrated to be 10%–15% higher under direct light compared to equivalent amounts of diffuse light (Brodersen et al., 2008). However, diffuse light is reported to increase photosynthesis of leaves that are shaded by other leaves in the canopy by up to 55%, which can increase whole-plant photosynthesis as reported for high-wire cucumber cropping system in a greenhouse setting (Chen et al., 2014). Thus, plants might become disadvantaged or might profit from increasing shares of diffuse radiation under solar panel depending on their canopy structure. Furthermore, plants show several morphological responses to shading, which affects plant canopy structure. These responses include the elongation of stems and petioles, changes in leaf orientation towards more upward oriented leaves, enhanced upwards oriented growth and reduced branching (Franklin, 2008; Franklin & Whitelan, 2005; Morgan et al., 1980; Mullen et al., 2006). All these responses reduce canopy density and, thus, increase light interception within the canopy resulting in an increased relative share of light being available for lower canopy leaves. Thus, increased shares of diffuse radiation favouring whole plant productivity might compensate for yield reductions caused by shading in agrivoltaic systems. Additionally, new PV module technologies, for example, the application of light diffusion films, have been shown to improve lettuce growth and could, thus, represent a strategy to reduce negative effects of shading on crop growth below PV modules (Tani et al., 2014).

Besides changes in total light quantity and quality, also temporal light availability is strongly modulated in agrivoltaic systems. In comparison to open field conditions, temporal and spatial variability in light availability is significantly higher in agrivoltaic systems (Santra et al., 2021). Such strong fluctuations in light availability have been shown by several studies to significantly reduce productivity of crops (Taylor & Long, 2017; Wang et al., 2020). Generally, the net effects of shading on crop growth will strongly depend on the architecture and light use efficiency of the crop canopy, as well as their physio- and morphological adaptability to changing light conditions. These crop-specific differences have to be the focus of future research in the field of plant ecology and crop sciences focusing on agrivoltaics (see Table 1 for a summary of the pressing research questions).

TABLE 1 Summary of pressing research questions/needs tackling the effects of agrivoltaics (APV) on microclimate, crop growth and yield as well as local biodiversity. For each question/need, we provide non-exhaustive information on the variables and approaches to measure/use.

Research questions/needs	Variables to measure/use	Approach
Effect of APV on crop yields	Crop yield (fresh and dry biomass)	Field measurements with high spatial resolution representative for the conditions in the APV system.
Effect of APV on yield quality	Contents of proteins, carbohydrates, raw fibre, etc.	Field measurements with high spatial resolution representative for the conditions in the APV system.
Effect of APV on crop morphology	Root/shoot biomass, crop height, total leaf area, leaf area index, etc.	Field measurements with high spatial resolution representative for the conditions in the APV system.
Effect of APV on crop development	Phenological development (e.g., BBCH)	Field measurements in APV systems with high spatial and temporal resolution.
Effect of APV on water and near-surface energy fluxes	Radiation incl. PAR, water availability/demand (i.e., soil water availability and atmospheric water demand, VPD), air and soil temperature	Field measurements in APV systems with high spatial and temporal resolution.
Crop-specific responses to shading	Specific leaf area, chlorophyll content, light response curves, chlorophyll fluorescence	Field measurements in APV systems with high spatial and temporal resolution; trait screening under standardized (greenhouse) conditions.
Crop-specific responses to altered water availability and demand	Plant water status (water potential), transpiration, stomatal conductance, water use efficiency, stomatal behaviour (e.g., iso- and anisohydric)	Field measurements in APV systems with high spatial and temporal resolution.
Crop-specific responses to altered air and soil temperatures	Indicators of heat stress, for example, via chlorophyll fluorescence measurements	Field measurements in APV systems with high spatial and temporal resolution.
Crop-specific responses to altered nutrients availability	Soil nutrient concentrations; C, N, P concentrations in different crop organs (roots, stem, leaves, fruits)	Field measurements with high spatial resolution representative for the conditions in the APV system.
Global repository on agrivoltaics crops	Synthesis of crop-specific, carbon, water and nutrient responses from field investigations and trait screening	Open-access data repository
Development of agrivoltaics crop models	Crop-specific, carbon, water and nutrient responses from field investigations and trait screening for model parametrisation and evaluation	Model development using FAIR data standards (i.e., via Git).
Effects of APV on local biodiversity	Monitoring of different groups of organisms (plants, vertebrates, invertebrates, soil microorganisms)	Monitoring in APV systems with spatial and temporal resolution depending on the monitored organisms.

Abbreviations: APV, agrivoltaics; BBCH, Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie; FAIR, findability, accessibility, interoperability and reuse; PAR, photosynthetically active radiation; VPD, vapour pressure deficit.

2.2 | Air temperature

Studies assessing the effect of agrivoltaics on air temperature show contrasting results. Although some studies noted a significant drop in air temperature (Weselek, Bauerle, Hartung, et al., 2021), others found no difference in daily or mean air temperature under the solar panels at 0.5 or 2 m height aboveground, respectively (Adeh et al., 2018; Marrou, Guilioni, et al., 2013). Lowered air temperature in agrivoltaic systems will become beneficial in dry and hot years, resulting in enhanced leaf photosynthesis and reduced leaf senescence under shading, which will consequently increase yield potentials (Siebert et al., 2014). Kittas et al. (2015) showed, however, that canopy surface temperature more than air temperature is reduced, resulting in reduced evaporative demands with positive effects on crop growth and, thus, yield. Assessing canopy temperature in future studies may therefore be a useful approach to assess temperature effects in agrivoltaic systems.

Diurnal variations in soil and air temperatures are significantly increased in agrivoltaic systems. However, effects on crop yield and quality are still unclear. Marrou, Guilioni, et al. (2013) concluded that the day-night-amplitude of crop temperature was reduced below PV panels. However, higher night-time temperatures can enhance respiration, reducing crop yield, but may on the other hand reduce frost damage in temperate climates, improving crop yield (Sadok & Jagadish, 2020). The effect of altered air temperature on nutritional quality is, thereby, crop dependent and may, for example, change carbohydrate composition and oil content in soybean, as well as oil composition in wheat (Williams et al., 1995; Wolf et al., 1982). Data on the effect of agrivoltaics on crop quality is scarce and usually is not focussed on temperature effects. Mineral and protein content in celeriac, cultivated in an agrivoltaic system showed, for instance, no treatment effect, whereas artificial shading in a field trial in France increased protein content in durum wheat (Dufour et al., 2013; Weselek, Bauerle, Zikeli, et al., 2021).

2.3 | Soil water availability and evaporative demand

Water is an essential resource for and component of plants, not least, because plants inevitably lose water when they assimilate carbon from the atmosphere to maintain growth. Plants counteract drought stress under decreasing soil water availability and increasing evaporative water demand by decreasing transpirational water loss through stomata closure. However, stomata closure directly interferes with photosynthetic carbon acquisition as CO_2 is taken up via the stomata. Thus, productivity can be reduced by drought stress with species-specific variation among crops. These species-specific differences in the trade-off between water loss and productivity will be directly linked to the stomatal behaviour of the different crops (i.e., isohydric vs. anisohydric behaviour), but this is insufficiently investigated so far for agrivotaic systems (see Table 1).

Drought stress in plants generally emerges when water supply from the soil is low (i.e., edaphic drought), atmospheric demand for water is high (i.e., atmospheric drought) or a combination of both occurs (Passiura, 1982). This is conceptualized in the soil–plant atmosphere continuum (Philip, 1966). Agrivoltaic systems change both, soil water availability through either rain shading or reduced evapotranspiration, as well as evaporative water demand of the atmosphere (AL-agele et al., 2021; Juillion et al., 2022). Reduction of evapotranspiration is commonly observed in agrivoltaic systems (Adeh et al., 2018; AL-agele et al., 2021; Barron-Gafford et al., 2019; Marrou, Wery, et al., 2013). This reduces atmospheric water demand, often quantified as vapour pressure deficit (VPD) and will ultimately increase water use efficiency of crops growing underneath solar panels as shown, for example, for agave plants and pasture grass species (Adeh et al., 2018; Ravi et al., 2014).

The modifying effect of agrivoltaics on soil–plant-atmosphere water relations and the fundamental trade-off that exists between transpirational water loss and photosynthetic carbon gain can lead to different net effects of agrivoltaics on crop growth depending on the surrounding environmental conditions (see Figure 2). Whereas shading by agrivoltaic systems can reduce growth in years with sufficient precipitation, thus high soil water availability but low atmospheric water demands (Figure 2a), shading can have positive effects in years with low precipitation because of lowered evaporation and, thus, reduced plant water loss (Figure 2b). Such contrasting effects are reported, for example, by Weselek, Bauerle, Hartung, et al. (2021) for winter wheat (−19 vs. +3% in a dry vs. a wet year) and potatoes (−20 vs. +11%) in Southern Germany. Drought attenuation effects of agrivoltaic systems during hot summer conditions are furthermore reported for Massachusetts (Apostoleris & Chiesa, 2019). The strength of this attenuation effect will, however, vary depending on the light and water use efficiency of the specific crop.

Generally, knowledge about the magnitude of the drought attenuation effect as well as about small-scale differences within the agrivoltaic system (i.e., fully vs. partly shaded areas) is still missing for the majority of crops (see AL-agele et al., 2021 for tomatoes). This knowledge will, however, be mandatory to adapt crop models to agrivoltaic settings and to implement crop-specific water management, that is, by automated irrigation systems fed by water collected on the panels during precipitation events (water harvesting; Sevik & Aktaş, 2021) and stored for drought stress periods.

2.4 | Agronomic consequences

In summary, crop yield and, thus, the agricultural production of agrivoltaics depends on the species-specific responses of crops to the environmental conditions (i.e., light, water and nutrient availability) modified by the respective agrivoltaic systems. These responses ultimately depend on functional characteristics of the crops grown underneath the PV system such as water and nutrient use efficiency or shade tolerance (Feuerbacher et al., 2021; Laub et al., 2022). Generally, winter crops such as pea and wheat crops have been demonstrated to benefit less from shading in agrivoltaics systems than summer crops (Dupraz et al., 2011). However, studies on the effects of agrivoltaics on plant growth are generally lacking, and the existing ones are often very case-specific. Laub et al. (2022) provide a first comprehensive overview about the shade tolerance of temporal crops and, thus, about the potential suitability for agrivoltaics and agroforestry systems. Most of the crops reported by Laub et al. (2022) tolerate shading up to 15% of the unshaded condition without significant yield loss. Berries, fruits and fruity vegetables are reported to even benefit from shading up to of 30%. Forages, leafy vegetables, tubers and root crops as well as C_3 cereals were reported to suffer from shading with a less than proportionate crop yield loss. C_4 plants such as maize as well as grain legumes were reported to suffer most from shading with strong crop yield losses even for low degrees of shading (Laub et al., 2022). However, alteration in microclimatic conditions were not considered in this meta-analysis, suggesting that even crops evaluated to be not suitable for agrivoltaic systems based on their light demand might profit from shading in a drying world. This can be supported by findings of Amaducci et al. (2018), where even maize as a light demanding C_4 plant has been shown to profit from shading in agrivoltaic systems under drought stress conditions. The drought attenuation potential of agrivoltaics therefore differs not only in space and time but also depending on the selected crops. This can be related to increased water use efficiency in such systems, which could additionally be improved through exploiting the rain water harvest potential of agrivoltaics (Adeh et al., 2018; Barron-Gafford et al., 2019; Chekired et al., 2022). Besides crop choice, general climate conditions of the specific cultivation period and the geographical location of the agrivoltaic system as well as its technical specifications, that is, panel density, and the design itself (e.g., horizontally vs. vertically stilted) affect availability and spatial homogeneity of radiation and water, and, thus, crop yields (Imran & Riaz, 2021). However, far more empirical research and mechanistic understanding on the interactions between different types of PV systems and crops under varying environmental conditions is needed to fully evaluate this crop-specific effects of agrivoltaics.

3 | THE GLOBAL POTENTIAL OF AGRIVOLTAICS TO ATTENUATE DROUGHT EFFECTS ON CROP YIELD

Based on the effects of agrivoltaics on microclimate and crop growth, which we summarized in the previous paragraphs, we conclude that shading by agrivoltaics will reduce crop yield in comparison to maximum possible yield in open field conditions under well-watered conditions due to light limitation of photosynthetic carbon gain, thus productivity (Figure 2a), but can facilitate growth under drought conditions due to the reduction of evapotranspiration in contrast to strong, drought induced yield reductions under unshaded, open field conditions (Figure 2b). Thus, agrivoltaics can help to stabilize crop yield under increasing, temporal variability of water availability as a major symptom of global climate change (Agostini et al., 2021). This yield stabilization effect of agrivoltaics has been reported, for example, by Amaducci et al. (2018) for maize and seems to become especially important under extremely dry conditions or when irrigation is not available. We argue that this stabilizing effect on crop yield qualifies agrivoltaics to be a promising form of dual land use to attenuate drought effects on crop production and, thus, to foster resilience of agricultural production in a drying world. Here, we try to asses this attenuation potential on a global scale by combining information on the PV power potential and climatic aridity. PV power potential thereby quantifies the power production potential for a PV power plant in kilowatt-hour per kilowatt-peak with free-standing fixed-mounted c-Si modules, mounted at optimum tilt to maximize yearly PV production (https://solargis.com). Aridity is quantified by an aridity index calculated from mean annual precipitation divided by mean annual potential evapotranspiration (http://www.cgiar-csi.org). Climate data as basis of this index originates from the WorldClim Global Climate Database with a spatial resolution of 30 arcsec (~1 km at the equator) covering a time span of 30 years (1970–2000, http://WorldClim.org). Both indices, PV power potential and climatic aridity, were subsequently standardized to values between 0 (low values) and 1 (high values), thus with equal weights. Attenuation potential as the product of both standardized indices therefore also varies between 0 (no potential) and 1 (global maximum potential, see Figure 3).

Based on our analyses, drought attenuation potential of agrivoltaics seems to be especially promising in the drought prone regions of the world such as the Western United States, Eastern and Southern Africa, the Arabian Peninsula, the Middle East, India and Australia (Figure 3). This drought attenuation potential will be especially relevant for drought prone countries with massive population growth and changing climate such as India where available land for food and energy production is getting increasingly sparse (Mahto et al., 2021). Agrivoltaics will not only be beneficial to attenuate climate change effects in regions already classified as arid but will also especially become relevant for regions that are experiencing an increasing shortage in water with an expected increased severity in the future, such as large parts of the Mediterranean Regions across the world (Figure 3; Muñoz-García & Hernández-Callejo, 2022).

Agrivoltaics have been already realized to provide a strategy to fight desertification as reported by Williams (2022) for China—a fact that is consistent with the high attenuation potential we mapped for the peripheral regions of all big deserts of the world (Figure 3). Incentivizing agrivoltaics in regions with groundwater shortage has been argued to be able to reduce groundwater depletion and, at the same time, reduce CO_2 emission from power production to counteract climate change (Parkinson & Hunt, 2020). Furthermore, agrivoltaics can help to reduce soil salinization through reduction of evaporation—a common feature of irrigated agricultural areas in arid regions (Meitzner et al., 2021). Comparing our map with of the systematic review of Mamun et al. (2022) on the current global distribution of agrivoltaic research highlights that the majority of research and agrivoltaic systems is currently located in areas with lower drought attenuation potential such as Central Europe. This emphasizes the unexploited potential of agrivoltaics especially in the Global South.

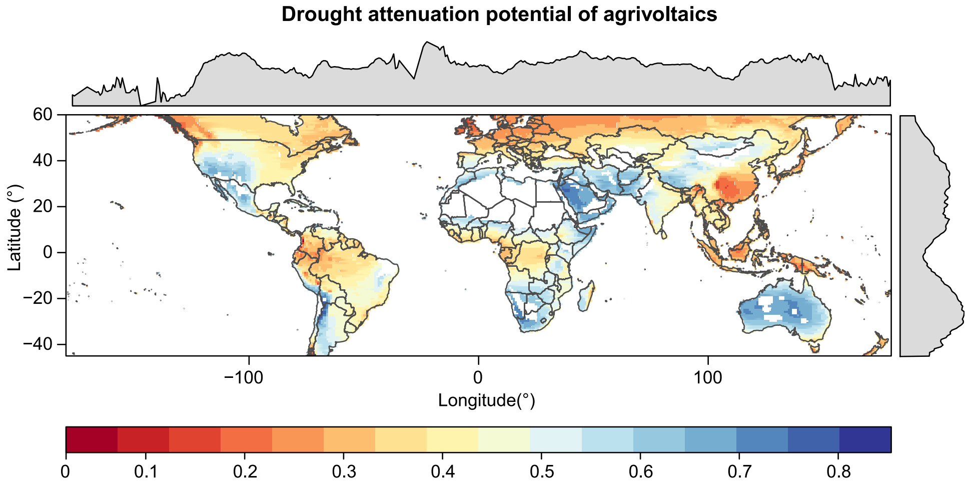

FIGURE 3 Global potential of agrivoltaics to attenuate negative drought effects on crop yield. Attenuation potential is calculated as the product of the photovoltaic power potential (https://solargis.com/maps-and-gis-data/download/world) and a drought index (i.e., the global aridity index calculated from mean annual precipitation divided by mean annual potential evapotranspiration, http://www.cgiar-csi.org), both standardized to values between 0 (low values) and 1 (high values), thus with equal weights. Attenuation potential varies between 0 (no potential) and 1 (global maximum potential) and is visualized by coloration (red to blue) as well as by histograms reflecting its longitudinal and latitudinal distribution. Desert areas are masked with white colour. This map reflects the potential for agriculturally used areas and does not imply that areas protected for biodiversity conservations or other forms of land use should be used for solar power production and/or should be transformed into agricultural land.

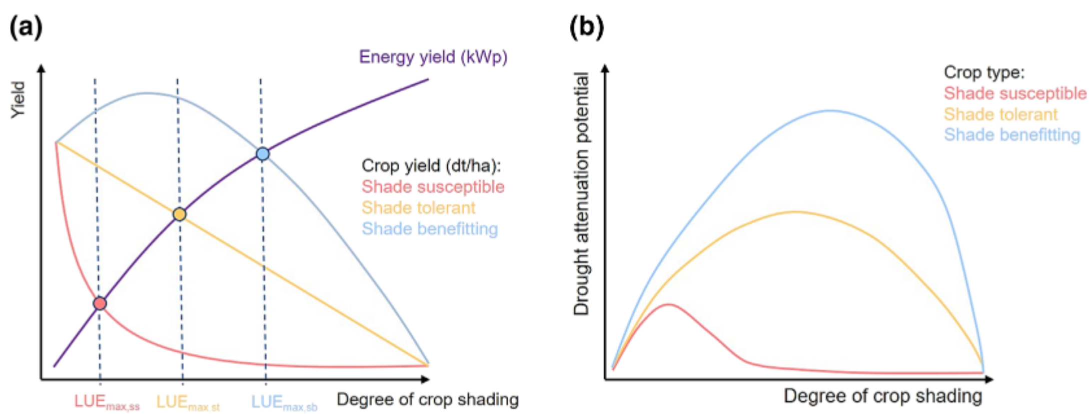

FIGURE 4 Conceptual figure on the trade-off between energy and crop yield as well as the drought attenuation potential for different degrees of crop shading in agrivoltaic systems. Crop yield (a) as well as drought attenuation potential (b) will differ for different types of crops, that is, shade susceptible (red lines), shade tolerant (orange lines) and shade benefitting crops (blue lines). The intersect between energy and crop yield represents maximum possible land use efficiency (LUE_{max}), that is, maximum combined energy and crop yield in agrivoltaic systems, which will differ for shade susceptible (ss), shade tolerant (st) and shade benefitting (sb) crops. Drought attenuation potential can be quantified as surplus crop yield in the system under varying degrees of crop shading in comparison to unshaded open field reference sites under drought conditions.

Our index of drought attenuation potential covers PV power potential and drought but does not cover response characteristics which crops use to reduce drought stress such as different degrees of water use efficiency. These crop-specific response characteristics in agrivoltaic systems must be the basis of detailed, mechanistic assessments and projections in the form of agrivoltaics crop models. However, crop-specific knowledge to adjust existing crop models to agrivoltaics settings is scattered or entirely lacking. Targeted research and synthesis of crop response traits in agrivoltaic settings is urgently needed to close these lack of knowledge (see Table 1).

4 | HOW TO TRADE OFF ELECTRIC POWER AND AGRICULTURAL PRODUCTION IN A DRYING WORLD

Agrivoltaics create an inevitable conflict between the amount of light being available for renewable energy production and the amount of light crops can use for growth. Increasing energy production by increasing panel density increases crop shading, which often will decrease crop yield (see Figure 4). Changes in crop yield by shading, however, differ between shade susceptible, shade tolerant and shade benefit crops sensu Laub et al. (2022), visualized by the differently coloured lines for crop yield in Figure 4a. This will directly affect maximum land use efficiency (LUE_{max}: maximum possible energy and crop production per unit of land) obtainable in agrivoltaic systems with lowest values for shade susceptible crop but increasing values for shade tolerant and shade benefitting crops (dashed, horizontal lines in Figure 4a). LUE can thereby be quantified, for example, as LER, that is, the sum of the yield ratios of dual land use (agrivoltaic system) to mono land use (separate production of energy and food). The trade-off between energy and crop production and consequently maximum, possible LUE will furthermore be modulated by the potential of agrivoltaics to attenuate effects of drought on crop production. This drought attenuation effect varies for different geographic regions (Figure 3) and will vary with the degree of shading realized in the agrivoltaic systems, which will affect soil water availability and evaporative demand of the atmosphere, thus, plant water status and growth. Drought attenuation potential will furthermore be different for shade susceptible, shade tolerant and shade benefiting crops with lowest attenuation potential for shade susceptible crops but highest potential for crops benefitting from shading (Figure 4b). The degree of crop shading realized in a certain agrivoltaic system might differ from LUE_{max} depending on how much weight will be put on energy vs. crop production. This weighting will be guided by political decisions on how to weight energy production versus food security and the corresponding incentives, but will ultimately be dependent on a set of economic, societal and ecological aspects, which will be discussed in the following sections.

4.1 | Economic aspects

Economic income generated by agrivoltaic systems through energy and agricultural production is one major aspect that will be used to define the degree of acceptable crop shading. Results from the United States show that solar energy production coupled with the agricultural production from shade-tolerant crops can increase the economic value of farms by 30% (Dinesh & Pearce, 2016). Cuppari et al. (2021) estimated net revenues of integrated power and agricultural production by agrivoltaics to increase by 300%–5000% relative to a farm-only scenario. They furthermore argue that agrivoltaics can diversify income streams, reduce revenue volatility and lift worst case net revenues by 48%–53% for crops being susceptible for climatic or market fluctuations, such as strawberries. To estimate the productivity of an agrivoltaic system, the LER can be implemented. Several studies showed that any agrivoltaic system results in LER values greater than 1, indicating a greater LUE (Amaducci et al., 2018; Dupraz et al., 2011; Trommsdorff et al., 2021). However, this concept can lead to misinterpretation of the actual agricultural contribution to the system, because crop yield and energy yield are equally weighted, and a high LER can be acquired even with low crop yields (Toledo & Scognamiglio, 2021).

Feuerbacher et al. (2021) estimated the agricultural contribution margin from land cultivated below agrivoltaic systems to decline by 40.3% for cereal and by 73.9% for vegetable farming. These declines are mainly caused by shading effects on crop yields, higher machinery and labour costs and the foregone agricultural contribution margins from area lost due to the mounting structure for the PV system. Based on these results, the authors conclude that the adoption of agrivoltaics will be more profitable for farms growing low-value crops such as cereals. They furthermore conclude that these reductions of the agricultural contribution margin might incentivize farmers to abandon agricultural production below agrivoltaic systems—a development that is already observable for solar power installations on agriculturally used land in Britain (Mathiesen, 2014). Social impact analyses show that clearly articulated, in the best case, legally binding standards are necessary to successfully disseminate agrivoltaics without facilitating subsidy abuse and pseudo-farming (Schindele, 2021). Standards are already implemented, for example, in Germany in the form of a technical rule (DIN SPEC 91434:2021-05). Although this technical rule is not legally binding, its requirements on agricultural production in agrivoltaic systems as well as the design of the system itself were, for example, consulted in the reform of the EU Common Agricultural Policy in Germany, which was implemented from 2023 onwards. This indicates the necessity of setting up such rules to define and delimit agrivoltaics from general ground-mounted systems, increasing adoption potential and acceptance. Such standards might be less important for shade tolerant perennial cash crops such as fruits or berries, which provide more economic income. However, farming of those special crops usually does not cover areas large enough to cover significant shares of energy demand by agrivoltaics but the large areas used for cereal and vegetable production will. Furthermore, adoption potential of agrivoltaics has been shown especially high for cereal and vegetable farming (Feuerbacher et al., 2021). Agrivoltaics has been furthermore argued to provide additional income and employment opportunities in rural areas currently experiencing overaging and out-migration as it is the case for many regions around the globe such as Japan (Elborg, 2015).

4.2 | Societal aspects

The degree to which agrivoltaics can be successfully implemented in our landscapes and contribute to drought attenuation will greatly depend on social circumstances in the local communities. PV adoption decisions have been reported to be strongly driven by economic and environmental considerations of the local community whereas ethical considerations showed less predictive power for the decision-making process (Brudermann et al., 2013). Brudermann et al. (2013) furthermore observed that agrivoltaics can open the door for transitions to renewable energy in rural areas—a fact that was also concluded by Pascaris et al. (2022) who observed that 81.8% of the people questioned responded to be more willing to support the implementation of PV in their community if it would be integrated in agricultural production. Acceptance for agrivoltaics was observed to be higher when the designed projects provide economic opportunities for farmers and the local community do not threaten local interests and ensure a fair distribution of the economic benefits (Pascaris et al., 2022). However, increasing implementation of agrivoltaics as a technical solution to attenuate climate change-related drought effects may weaken the willingness for lifestyle changes, which is an important basis to develop and implement effective climate change mitigation strategies as a basis for sustainable future development (Brudermann et al., 2013). Expansion of agrivoltaic systems will furthermore be hindered by landscape preservation reservations and public acceptance. Collaboration with local communities and authorities, early inclusion into the decision-making process and raising awareness for agrivoltaics and their potential to alleviate drought effects on food production can be the key to achieve acceptance (Formolli et al., 2022). Additionally, the design of the system should be adapted to the landscape (e.g., adapted to landscape orography) to reduce visual interference (Toledo & Scognamiglio, 2021).

4.3 | Biodiversity-related aspects

Besides its effects on the focal crops, agrivoltaics will affect other non-focal species and, thus, will interact with the local biodiversity. Graham et al. (2021), for example, reported floral abundance to increase and bloom timing to be delayed under partial shading in an agrivoltaics setting but do not affect pollinator abundance, diversity and richness. However, under full shading pollinator abundance, diversity and richness were significantly reduced, whereas floral abundance was comparable to unshaded conditions. Yet, far too little research exists on the effects of agrivoltaics on different groups of organisms including vertebrates (e.g., birds), invertebrates (e.g., insects) and microorganisms (e.g., soil fungi, pathogens) in the landscapes, leaving major gaps for upcoming research. These effects might turn out to be positive or negative depending on the groups of organisms and the environmental setting. Furthermore, landscape settings, that is, homogenous versus heterogeneous landscapes will affect the net outcome of agrivoltaics on local biodiversity. Based on the effects agrivoltaic will have on biodiversity, this technology could facilitate or diminish current efforts to reconcile agricultural production and biodiversity conservation. Thus, detailed understanding of the effects of agrivoltaics on biodiversity will be key when aiming for nature-based solutions in renewable energy and agricultural production (see Table 1).

5 | CONCLUSIONS AND RESEARCH NEEDS

Agrivoltaics has a high potential to attenuate negative effects of climate change, especially drought on crop yield and, thus, can help to increase resilience of agricultural production and food security under increasingly variable environmental conditions. This attenuation potential will vary across space and time depending on the climatic conditions and will differ depending on the crops grown in such kind of dual land-use systems. Drought attenuation potential will furthermore be affected by light and water being available for crop growth but also by crop-specific traits reflecting light and water use efficiency and stress. Knowledge on crop-specific response characteristics under agrivoltaic settings is essential to adjust existing crop models to agrivoltaic systems, which will allow for sound, quantitative predictions of the attenuation potential of agrivoltaics in a drying world. Such trait data will not only be useful to select the optimal crop for a desirable degree of crop shading under certain climatic conditions but can also help to develop smart agrivoltaic systems where real-time data on plant stress signals can be used to control panel orientation and thus shading. Generally, such data will help to exploit the full potential of agrivoltaics as a new form of agricultural production where the microclimatic conditions can be better controlled and partly decoupled from the increasingly harsher environment by fostering, at the same time, a global, sustainable energy transition.

AUTHOR CONTRIBUTIONS

Andreas H. Schweiger and Lisa Pataczek jointly developed the idea for this study; Andreas H. Schweiger performed the analyses and led the writing with major input by Lisa Pataczek.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ORCID

Andreas H. Schweiger https://orcid.org/0000-0003-2656-5918
Lisa Pataczek https://orcid.org/0000-0003-4206-7791

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