Received: 24 May 2023 | Revised: 9 November 2023 | Accepted: 26 November 2023

DOI: 10.1002/ppp3.10481

OPINION

Plants People Planet PPP Open Access

Conservation agrivoltaics for sustainable food-energy production

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Funding information
National Institute of Food and Agriculture, Grant/Award Number: 2021-68012-35898

Societal Impact Statement

Transformative agricultural strategies like agrivoltaics (AV) are essential for addressing the pressing global issues of sustainable energy and food production in a changing climate. Conservation-agrivoltaics (Conservation-AV) provides the potential to meet these needs while reinforcing natural resources and protecting the environment. It could enhance the ecological benefits of AV by improving soil health and biodiversity. It could create economic opportunities for farmers and increase the resilience and diversity of food crops under changing climate conditions. Furthermore, it could inform stakeholders about the benefits and challenges of implementing conservation agriculture management practices (CAMP) in AV and encourage further exploration and adoption of this innovative approach.

Summary

Transformative strategies in agriculture are needed to address urgent global challenges related to energy and food production while reinforcing natural resources and the environment. Agrivoltaics (AV) has emerged in the past decade as one solution to this fundamental challenge of improving energy and food security. AV is defined as the co-location of solar photovoltaic (PV) panels and crops on the same land to optimize food and energy production simultaneously and sustainably. Here, we propose that AV, together with conservation agriculture management practices (CAMP) strategies can help to intensify food security and energy production while reinforcing natural resources and the environment. Our main assertions in this opinion article are that: (1) AV systems need to overcome several agronomical, environmental, and ecological challenges to intensify food and energy production sustainably; (2) CAMP applied to AV systems can preserve the environment and ensure climate-resilient food production; (3) implementation of CAMP in AV can lead to long-term carbon sequestration, lower greenhouse gas emissions, and maintain or increase crop yields while preserving soil health and biodiversity; and (4) adoption of CAMP in AV can bring economic benefits, although challenges need to be overcome. This opinion article proposes a new ecosystem approach to integrate renewable energy and sustainable food production and encourages research on the effects of CAMP on AV systems.

KEYWORDS

agriculture, agrivoltaics, conservation, global change, renewable energy, sustainability

1 | INTRODUCTION

The task of securing and enhancing both energy and food production amidst a fluctuating and uncertain climate is often impeded by the traditional view of land use, which suggests a "zero-sum-game" competition between certain types of renewable energy, particularly solar photovoltaic (PV) installations and food production (Barron-Gafford et al., 2019). Agrivoltaics (AV), the combination of solar PV and food production on the same land (Barron-Gafford et al., 2016, 2019; Dupraz et al., 2011), has emerged in the past decade as one solution to the fundamental challenge of improving both energy and food security while redefining land management strategies to limit global warming below 2°C. The effectiveness of this novel system as a climate mitigation strategy will, however, depend strongly on how the underlying crops are managed. While significantly increasing yields, traditional intensive agriculture produces 11% of global greenhouse gas (GHG) emissions and degrades soil health (Gliessman, 2014; Gomiero, 2019; Lal et al., 2007; Montgomery, 2007; Nearing, 2013). In addition to meeting food and energy demands, AV systems must effectively mitigate climate change, enhance ecosystem resilience, and optimize natural resources.

In this opinion article, we highlight the importance of adopting some well-characterized conservation agriculture management practices (CAMP) to AV to strengthen the preservation of the environment and climate-resilient food production. These consist of a series of strategies that promote maintaining a permanent soil cover, minimum soil disturbance, and enhancing biodiversity (Gomiero, 2019; Islam & Reeder, 2014; Khosa et al., 2011; Stavi et al., 2012). These practices are gaining global importance as an alternative to input-intensive conventional agricultural production due to their effectiveness in climate change mitigation, system resilience enhancement, and natural resources optimization (Islam & Reeder, 2014).

Despite the growing adoption of CAMP globally, the effectiveness of this practice in AV remains unexplored. The adoption of AV could enhance the environmental and ecological sustainability of agricultural land compared with conventional solar energy deployment (i.e., PV array systems) and crop monoculture alone as recently reported (Gomez-Casanovas et al., 2023). However, with notable exception (Amaducci et al., 2018; Imran et al., 2020; Perna et al., 2019; Riaz et al., 2022; Valle et al., 2017), agricultural AV systems are often managed using conventional agricultural practices (Agostini et al., 2021; Dinesh & Pearce, 2016; Jo et al., 2022; Malu et al., 2017; Moreda et al., 2021; Patel et al., 2018; Proctor et al., 2021; Schindele et al., 2020). Conventional agricultural practices can decrease biodiversity and soil carbon storage while increasing the emission of GHGs and nutrient runoff (Gliessman, 2014; Gomiero, 2016; Lal et al., 2007; Montgomery, 2007; Nearing, 2013). In this opinion article, we outline the challenges and benefits of AV and propose that the AV system with improved CAMP can promote long-term carbon storage, reduce GHG emissions, and maintain or increase crop yields while preserving soil health and biodiversity. We, furthermore, outline the need for research to investigate the potential of AV systems with improved CAMP to sustainably intensify food and energy production, as well as the main economic benefits and challenges that can result from CAMP adoption and implementation in AV. Thus, this article will provide insights into the potential of AV with CAMP to address global challenges such as climate change, food security, and sustainable land management. It will also inform policymakers, farmers, and other stakeholders about the benefits of CAMP in AV (Conservation-agrivoltaics [Conservation-AV]) and pave the way for their wider exploration and adoption.

2 | CHALLENGES AND POTENTIAL BENEFITS OF AGRIVOLTAICS: BALANCING TRADE-OFFS AND ENVIRONMENTAL CONSIDERATIONS

The use of PV renewable energy has been identified as a key strategy to reduce fossil fuel combustion while using a lower water footprint compared with other renewable energies (e.g., hydropower and bioenergy (Apollon et al., 2021). Utility-scale solar energy deployment, however, competes with food production and often reduces biodiversity (Allardyce et al., 2017; Barron-Gafford et al., 2016; Böhm et al., 2022). In this context, AV reduces the competition for land resources and with thoughtful management can enhance biodiversity compared with PV alone (Amaducci et al., 2018; Barron-Gafford et al., 2019; Feuerbacher et al., 2021; Laub et al., 2022; Schweiger & Pataczek, 2023; Weselek, Bauerle, Hartung, et al., 2021). Further, AV consistently increases the efficiency of land use or land productivity with an average land equivalent ratio (LER). LER is defined as:

$$LER = \left(\frac{P_{AV}}{P_{mono}}\right) + \left(\frac{Y_{AV}}{Y_{PV}}\right),$$

where P is plant productivity in AV (P_{AV}) or a monoculture (P_{mono}), and Y is energy productivity in an AV (Y_{AV}) or dedicated PV (Y_{PV}) setting. If

LER > 1, the AV system is more efficient in terms of combined P and Y output relative to either a crop monoculture alone or a PV system alone over the same land area. The combination of PV and crops on the same land has been shown to achieve a higher LER of about 1.5 ± 0.3 compared with crop monoculture or PV arrays alone, suggesting that the AV system can provide 50% more total output (Gomez-Casanovas et al., 2023).

AV has the potential to provide synergistic advantages across technological, ecological, environmental, and economic domains while also bolstering the climate resilience of our energy and food systems compared with utility-scale solar energy and conventional agriculture. There are, however, significant challenges to overcome (Gomez-Casanovas et al., 2023; Sturchio & Knapp, 2023). First, there is uncertainty about the extent that AV will impact the yield of different crops, and how the effect on yield will vary in different climate zones and soil types. This suggests that management practices designed to optimize crop production will play a prominent role in mitigating the trade-offs between solar energy production and plant productivity (Weselek et al., 2019). Second, the use of renewable energy AV deployment has the potential to help mitigate CO_2 emissions from fossil fuel combustion given the electricity generated from AV systems. However, potential increases in soil moisture and nitrogen availability in AV systems compared with PV alone (Armstrong et al., 2014) could stimulate the emission of N_2O and CH_4 from soils, although the impact of AV deployment on these potent GHGs and the overall climate mitigation potential of AV is still uncertain (Gomez-Casanovas et al., 2023). Third, solar panels can affect local air temperatures (Gomez-Casanovas et al., 2023). Some studies have shown that PV deployment can increase the local air temperature by absorbing and radiating heat, a phenomenon called the PV heat island effect (Masson et al., 2014; Weselek, Bauerle, Zikeli, et al., 2021), whereas other studies suggest that ambient temperature decreases or remains unaffected (Adeh et al., 2018). In cases when PV induces a heat island effect, plants grown under the solar panels, as is the case with AV, could reduce this effect by evaporating water and cooling the surface (Gomez-Casanovas et al., 2023).

PV panels alone significantly impact the distribution of rain and associated soil erosion (Choi et al., 2020; Weselek, Bauerle, Hartung, et al., 2021). These impacts can be both positive (in AV systems) or negative (in PV alone), depending on the system. Alteration in the distribution and flow of rainwater associated with physical barriers can change the way rainwater is distributed across the field, which has been reported in PV systems (Armstrong et al., 2014; Choi et al., 2020; Weselek, Bauerle, Hartung, et al., 2021). The removal of vegetation around and underneath PV arrays increases runoff and soil erosion (Choi et al., 2020; Weselek, Bauerle, Hartung, et al., 2021). On the other hand, the PV panels in AV systems have positive impacts on soil erosion reduction (Armstrong et al., 2014; Choi et al., 2020; Weselek, Bauerle, Hartung, et al., 2021), reducing soil erosion by up to 60%, compared with open-field agriculture by reducing the impact of raindrops on the soil surface (Weselek, Bauerle, Hartung, et al., 2021).

3 | CONSERVATION AGRICULTURE MANAGEMENT PRACTICES (CAMP) CAN BENEFIT ECOSYSTEM SERVICES AND OPTIMIZE THE PERFORMANCE OF AGRIVOLTAICS SYSTEMS

Conservation agriculture (CA) consists of a set of management practices to minimize soil structure disturbance, conserve soil water, enhance biodiversity, promote cover crops, and optimize crop rotation all while focusing on improved crop yields (Altieri et al., 2005; Hobbs, 2007), see (Figure 1). CA principles can be applied universally to all agricultural landscapes or land uses with corresponding practices adapted at a local scale. CA principles can be applied to AV as a novel approach (Conservation-AV) to sustain the resilience of renewable energy and food production security.

Conventional agricultural practices in AV systems may include irrigation, soil fertility, weeds management, and pest control. As conventional agricultural management is based on soil tillage as one of its primary operations, there is evidence of potential negative effects of tillage on soil structure under conventional systems (Islam & Reeder, 2014). Research suggest that tillage can lead to soil compaction and reduced permeability, resulting in an increased runoff, soil erosion, and nutrient losses (Gliessman, 2014; Gomiero, 2016; Lal et al., 2007; Montgomery, 2007; Nearing, 2013), see (Figure 2). Additionally, tillage has been linked to decreased soil organic matter, which can further reduce soil fertility (Feller et al., 2020; Hassink, 1995; Huggins & Reganold, 2008; Six et al., 2000; West et al., 2002). Due to the harmful effect of tillage, no-till practices are increasingly implemented in agricultural fields (Islam & Reeder, 2014). The effects of tillage under AV systems are unknown.

As of today, any potential differences between CAMP in AV systems and AV without CAMP would be purely hypothetical because of the scarcity of available data (Figure 1). Here, we used well-characterized and mechanistic knowledge of how CAMP (Hobbs, 2007; Hobbs et al., 2008) affects several key sustainability metrics in conventional non-AV systems to hypothesize how these strategies could impact sustainability outcomes in AV systems (Conservation-AV) to sustain the resilience of renewable energy and food production while maintaining soil biodiversity (Figure 1):

- Zero tillage or direct seeding. This CAMP involves growing crops without mechanical preparation of the seedbed or the soil alteration from the previous crop and may include cutting or crushing weed and crop residue, spraying herbicides for weed control, or sowing directly through the cover layer. With this strategy, all crop residues remain in the field and the fertilizer is applied during planting. Relative to conventional management, zero tillage in an AV system can help mitigate GHG emissions (Blair et al., 1995), and have other benefits through its effects on biological diversity, soil properties, and water regulation (Table 1). Given the scarcity of data available in AV systems, we predict that zero tillage in an AV system with CAMP could reduce the soil disturbance and erosion caused by the installation and

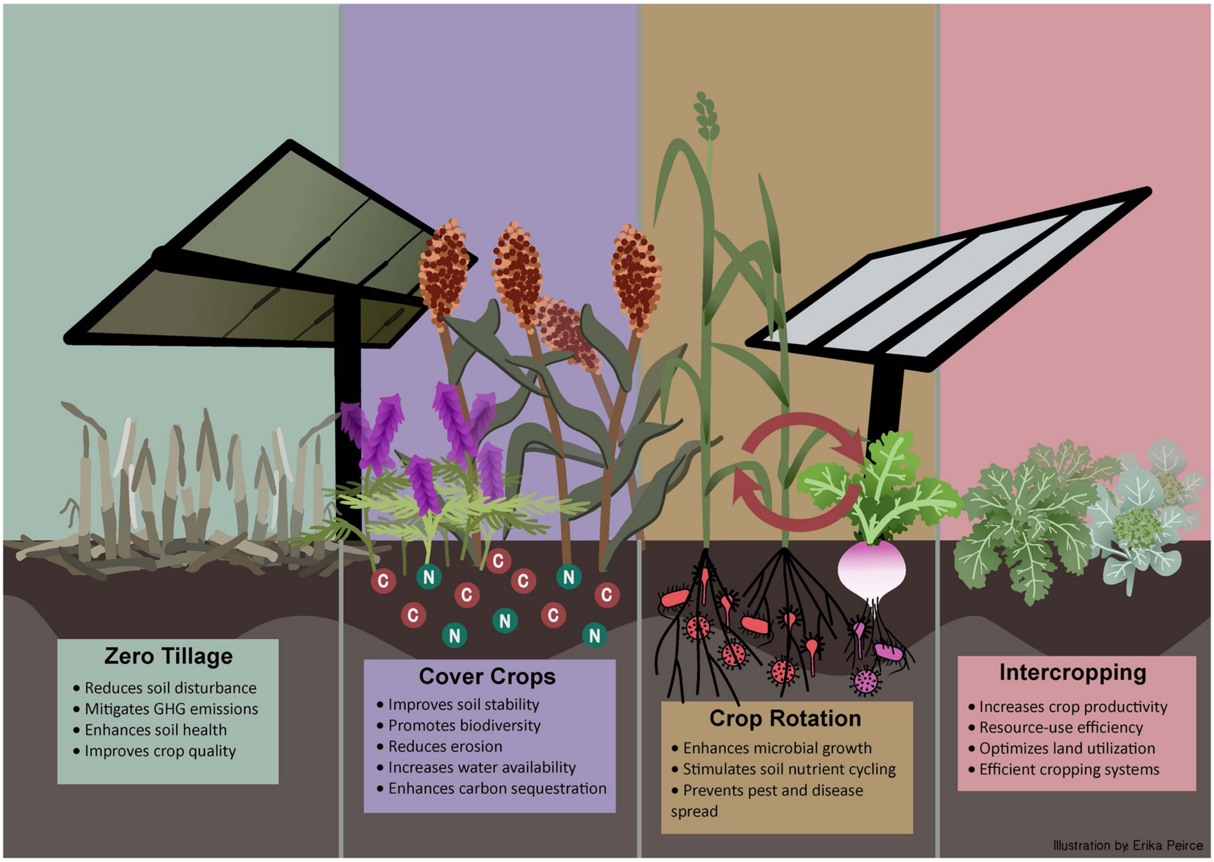

FIGURE 1 Summary of well-characterized and mechanistic knowledge of conservation agriculture management practices' (CAMP) effects on several key sustainability metrics in conventional non-agrivoltaics (AV) systems and prediction of these strategies' benefits in enhancing agrivoltaic system performance. All the benefits of CAMP interact; this summary considers benefits related to minimal soil disturbance, direct seeding, permanent cover cropping, crop rotation, and intercropping, all together in the case of increasing soil productivity.

maintenance of solar panels, which could otherwise expose the soil to water and wind erosion and release carbon dioxide into the atmosphere. It could, additionally, enhance the soil organic matter and microbial activity by retaining the crop residues and weed cover on the soil surface, improving soil structure, water retention, nutrient cycling, and carbon sequestration as shown in studies focusing on CAMP strategies in non-AV systems. Further, zero tillage could increase crop yield and quality by creating a microclimate under the solar panels that reduces water stress, temperature fluctuations, and pest infestation. From an entomological point of view, zero tillage can impact pest infestation in several ways. It primarily reduces weed growth as the soil remains undisturbed, preventing weed seeds from surfacing and germinating, unlike traditional tilling methods. This undisturbed state of soil also disrupts the life cycles of certain pests and diseases that thrive in regularly disturbed soil, thereby reducing pest populations. Furthermore, zero tillage enhances the populations of beneficial organisms in the soil, such as earthworms and other insects that prey on crop pests. Thus, zero tillage can be an effective strategy for pest management when used in conjunction with other CAMPs like crop rotation and cover crops (Altieri et al., 2005).

- Cover crops. This CAMP improves soil stability not only by enhancing soil properties but also by promoting increased biodiversity in the agroecosystem. Cover crops have economic value as they are used as food and energy feedstock and in regions characterized by low biomass production and soil erosion. They are beneficial because they protect the soil during fallow periods by improving soil structure. Further, when cover crops are incorporated into soil, tissue decomposition functions like organic biofertilizers (Mann et al., 2002; Šimanský & Tobiašová, 2011; Yang & Wander, 1999) with potential to improve the availability and accessibility of nutrient uptake by plants (Abbey et al., 2019) and soil microbes, stimulating soil nutrient cycling (Bhardwaj et al., 2014; Parul Chaudhary et al., 2022). Cover crops in an AV system could provide more shade, reducing evaporation and erosion losses, and increasing water availability for the crops and microorganisms underneath the panels. Further, cover crops in these systems could improve the soil carbon sequestration and GHG mitigation by increasing plant production and organic matter input to the soil as demonstrated in studies focusing on non-AV systems, which could offset the carbon footprint of the solar panels and enhance soil quality and fertility. Cover crops could also increase plant diversity and resilience by introducing different plant species and functional groups that could

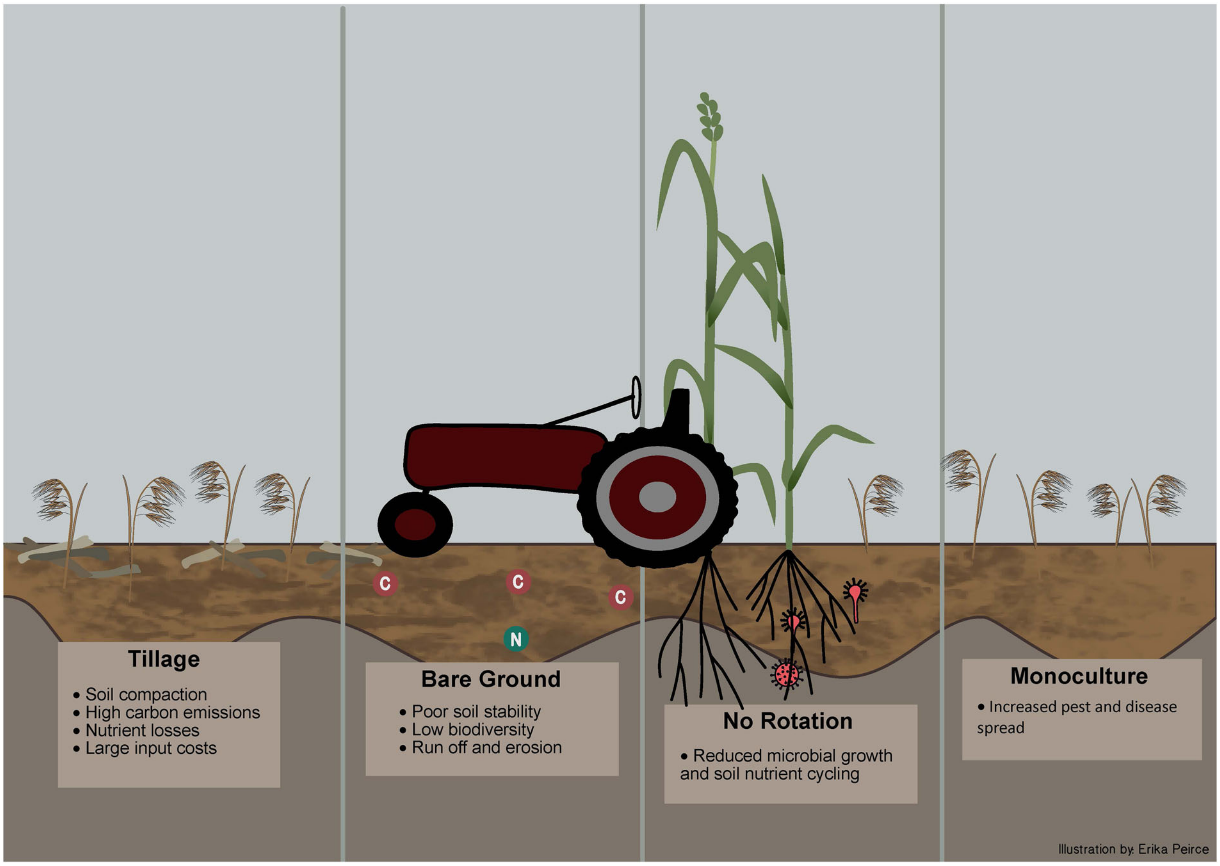

FIGURE 2 Overview of documented adverse impacts of conventional agricultural practices. Tillage can lead to soil compaction and reduced permeability, resulting in increased runoff, soil erosion, and nutrient losses. Bare ground, no rotation, and monoculture can result in poor soil stability, low biodiversity, low microbial growth and nutrient cycling, and increased pest and disease spread.

TABLE 1 Potential impact of diverse conservation agriculture management practices (CAMP) on several key sustainability metrics of agrivoltaics (AV) systems. CAMP includes direct seeding, enhanced soil coverage through cover cropping and intercropping, crop rotation, and water conservation practices. Sustainability metrics include biodiversity, yield, SOC, GHG regulation, water regulation. Positive (+) and negative (−) reflect increase or decrease of each specific metric, respectively, and "na" or blank space for no data available. Data shown in this table are non-AV systems. Because all the benefits of CAMP are interacted, this summarized consider benefits related to minimal soil disturbance, direct seeding, permanent cover cropping, crop rotation, intercropping and water conservation, all together in the case of increasing soil productivity.

CA practice	Biodiversity	Soil productivity	SOC	GHG regulation	Water regulation	PV heat island effect
Zero tillage	+[d,e]	+[d,e]	+[d,e]	+[d]	+[d,e]	na
Cover cropping	+[e]	+[d,e]	+[a,e]	+[b]	+[c,e]	na
Crop rotation	+[e]	+[d,e]	+[d,e]		+[e]	na
Intercropping		+[d]				na

Abbreviations: GHG, greenhouse gas; PV, photovoltaic.
[a](Bai et al., 2019; Poeplau & Don, 2015).
[b](Abdalla et al., 2019).
[c](Wang et al., 2021).
[d](Hobbs, 2007).
[e](Clapperton, 2003).

improve pest and disease resistance, weed suppression, and yield stability (Altieri et al., 2005).

- Crop rotation. This CAMP enhances microbial growth and soil nutrient cycling by providing diverse food sources to soil microorganisms. Moreover, a diversity of crops in rotation leads to diverse flora and fauna of the soil as roots excrete different organic substances that attract different types of bacteria and fungi, which, in turn, play an essential role in the transformation of these substances into nutrients available to plants (Bhardwaj et al., 2014; Chaudhary et al., 2022). Crop rotation also provides a crucial phytosanitary function as it prevents the transmission of specific pests and diseases from one crop to the next through waste (FAO, 2016; Reeves et al., 2016). In this light, crop rotation can be essential to support the sustainable production of food in the AV system. By rotating crops and introducing a diversity of plants, this practice can enhance soil health and ensure that pests and diseases are prevented from spreading in the AV system as shown in non-AV systems.

- Intercropping. This CAMP consists of the simultaneous or relay cultivation of multiple crops on the same field during a significant part of their growth cycle to exceed the crop productivity of standard monoculture systems (Li et al., 2020; Liebman, 1990). Intercrops, through niche partitioning, have high resource utilization efficiencies with solar radiation, water, and nutrients (Brooker et al., 2015; Cardinale et al., 2007). If diverse crops with varying light requirements are selected, intercropping in an AV system could increase light use efficiency and optimize the light distribution and capture under the solar panels, thereby increasing photosynthesis and consequently biomass production (Huss et al., 2022). Further, by selecting diverse crops with varying water and nutrient demands and uptake patterns, water use, nutrient stress, and competition can be reduced which could balance the soil moisture and fertility levels and avoid nutrient depletion or accumulation under the solar panels (Huss et al., 2022). Alternative cropping systems, such as maize and legume intercrops in non-AV systems, may potentially lead to higher yields and resource-use efficiency over monocultures (Pelech et al., 2021). Intercropping has documented entomological benefits such as reduced insect pest infestation and crop damage by disrupting host plant location, reducing host plant quality or increasing natural enemy activity (Huss et al., 2022). Intercropping can further assist disease management by creating a less favorable microclimate for pathogens or by increasing the diversity of plant defenses (Huss et al., 2022). However, intercropping may also increase the risk of disease transmission if plants from different families are grown together, which may reduce the effectiveness of crop rotation (Huss et al., 2022). Thus, intercropping can be used in AV systems to enhance productivity per unit of land area as well as water and nutrient use efficiency as seen in non-AV systems. However, empirical research comparing the efficiency of intercropping under AV is currently lacking.

Despite the scarcity of data available on AV systems with and without CAMP implemented, we predict that intercropping in an AV system can improve solar radiation, water, and nutrient utilization by beneficial neighbor interactions or by the dominance of a shade-tolerant crop species under the solar panels. It can improve resource use efficiency and enhance soil water holding capacity under solar panels and full sun areas.

Using these practices in AV systems may benefit local microclimates, affecting leaf temperatures, soil temperatures, and the water use efficiency of crops. Based on these above predictions from the proposed management practices, we hypothesize that using CAMP in an AV system will provide several additional benefits compared with an AV system without CAMP. These potential benefits include increased carbon storage, improved soil health and quality, reduced inputs such as water and fertilizer, enhanced biodiversity, increased crop yields, and more efficient water use. Additionally, CAMP may help reduce soil erosion, nutrient leaching, and the cost of inputs needed for agricultural production. Yet, there is not enough evidence to confirm or refute these hypotheses, so further research is needed to better understand the potential implications of CAMP on AV systems.

4 | THERE MAY BE ECONOMIC BENEFITS ASSOCIATED WITH IMPLEMENTING CAMP IN AN AGRIVOLTAICS SYSTEM

An important economic aspect of CAMP is the distribution of benefits and costs. Overall, the benefits can occur locally, nationally, and globally (Table 2). The benefits at the national level provide an essential argument for policy support at this level. For example, it was estimated that the realized erosion benefits (avoided losses from sheet, rill, and wind erosion) for the United States from the areas under conservation tillage ranged from US$90.3 million to US$288.8 million in 1996 (Uri, 1999; Young, 2001). Furthermore, from the farmer's perspective, the benefits of CAMP can be either on-site (private benefits) or off-site (reduced sediment pollution, carbon sequestration, etc.). Table 2 suggests that while many of the incremental costs associated with adopting CAMP occur at the farmer level, relatively few benefits do so, which is a concern for CAMP adoption (Pittelkow, Liang, et al., 2015; Pittelkow, Linquist, et al., 2015). This suggests a divergence between the social desirability of CAMP and its potential on-farm attractiveness.

Insights from the broader CA literature are also relevant for CAMP. Given the right farming conditions (such as farm size, management objectives, attitudes to risk and uncertainty, and willingness to make tradeoffs between stewardship and profits), conservation practices, including CAMP, can potentially contribute to farmers' welfare (Lalani et al., 2017). However, not all cases represent the right circumstances. A useful approach to address the limitations of CAMP is to recognize the heterogeneity of farming circumstances and make efforts to identify (using economic analysis) those cases where CAMP is adaptable. Efforts to promote CAMP should be focused on adoptable cases. Insights from CA suggest that research and extension institutions should avoid promoting CA as a one-size-fits-all solution to farmers' economic and natural resource challenges (Krishna et al., 2022; Pannell et al., 2014). While there appears to be a small cost advantage over conventional farming, the results are site-dependent. This highlights the importance of targeting CAMP and focusing extension on where CAMP benefits are most significant. If CAMP is preferable to other alternatives, providing monetary compensation to induce adoption may be an appropriate policy action.

TABLE 2 Potential benefits of conservation agriculture management practices (CAMP) in agrivoltaics systems. Blank space or "-"means no data available.

Benefits and costs/scale	Local	National/regional	Global
Benefits			
Reduction in input costs	X	-	-
Savings in time, labor, and machinery costs	X	-	-
Increase in soil fertility and long-term yields	X	X	X
Protection from soil erosion	-	X	-
Water quality improvements	-	X	-
Improved air quality	-	X	X
Reduction of carbon emissions	-	-	X
Biodiversity conservation	-	-	X
Costs			
Costs of specialized equipment	X	-	-
Short-term increase in pest pressure	X	-	-
Farmer learning costs and implementation	X	-	-
Cost of additional herbicides	X	X	-
Increased risk due to technological uncertainty	X	X	-

Source: Adapted from FAO (2001).

However, such a policy is unlikely to bridge the gap between the socially desirable levels of adoption and actual farmer behavior. Other factors also affect adoption. These factors include different farmer management objectives, stewardship motives, and other barriers or constraints that limit response to profit signals. Thus, there is a need for further research to investigate CAMP adoption.

With AV being a relatively new concept, empirical studies have not considered the economic benefits of adopting CAMP. The most relevant examples, therefore, come from the literature on conservation (Mulimbi et al., 2019; Pittelkow, Liang, et al., 2015; Pittelkow, Linquist, et al., 2015). For instance, Stonehouse (1995) simulated full-width no-plow and no-till in southern Ontario, Canada, and found that both provided modestly higher on-farm benefits than conventional tillage. The advantage of no-plow and no-till was even more significant, with off-site benefits included. The off-site benefits considered were downstream fishing and reduced dredging costs, which accounted for 43% and 10%, respectively, of the net social benefits from conservation tillage. This study showed that, despite marginally higher profits under CAMP, the inability to capture off-site benefits means few farmers will likely adopt CAMP. By contrast, the global concern about soil degradation helps motivate an argument for intervention at the international level. This argument arises not only from a concern about what is occurring within individual countries but also from the possible presence of regional or global costs imposed by soil degradation. This implies significant global benefits may be possible from adopting CAMP and other soil-enhancing technologies.

Overall, the net financial impact of CAMP on the individual farm scale appears positive. Several financial analyses of conservation tillage adoption, both in high-income countries (Stonehouse, 1997) or low- and middle-income countries (Sorrenson, 1997; Sorrenson et al., 1998) context, have found that it generally produces higher net returns relative to conventional tillage. This is true because of reduced costs for machinery, fuel, and labor, combined with unchanged or improved yields over time (Knowler & Bradshaw, 2007). Beyond conservation tillage, Knowler (2015) found that a great number of soil conserving practices typically produce net financial benefits for adopters, based on a meta-analysis of over 100 farm-level financial analyses from Sub-Saharan Africa and Latin America/Caribbean. Despite all the benefits Conservation-AV can bring to the AV system, its implementation will face some economic challenges (Knowler & Bradshaw, 2007). One of the biggest challenges of adopting CAMP in the AV system will be the discrepancy between its socially desirable nature and its appeal to individual farmers. Although society will benefit the most from its advantages, implementing CAMP in the AV system could incur various marginal costs at the farm level. These profitability-related challenges at the individual farm scale include the selection of plant species capable of adapting to the shade of PVs, interference of structures with crop production, reduction of planting area due to the installation of the systems, cost of construction of solar infrastructures, and commercial planning of these systems (Pascaris et al., 2020).

Given the lack of data available on CAMP, we lean on insights from wider CA to preview the farm-level adaptation to CAMP relative to conventional agriculture. Kiran Kumara et al. (2020) conducted a comprehensive meta-analysis of the economic and environmental benefits of CA in South Asia. The results of the meta-analysis showed that the cost of production in all the selected crops was significantly lower under CA. The cost was found to be significantly less in "zero or minimum-tilled" rice (−22%), wheat (−14%), legumes (−20%), and other crops (−10%). Further, the rice-wheat cropping system can save about 13% of the total cost (US$ 144/ha). CA was proven to be an economically feasible technology as the net returns were higher than the conventional tillage. The net returns under CA compared with traditional tillage were significantly increased by +12%, +32%, and +6%

for wheat, legumes, and other crop categories. Further, the adoption of CA in the rice-wheat cropping system resulted in an incremental benefit of US$ 34/ha (4%) than the conventional tillage because of the positive impact on the economics of wheat cultivation under CA (Kiran Kumara et al., 2020). The incremental net returns under CA were mainly due to cost savings and the positive yield effect of CA. Yields under CA were significantly increased by +3%, +2%, and +4% for wheat, maize, legumes, and oilseeds, except for rice, with a −3% yield reduction (Kiran Kumara et al., 2020).

From the same region, (Krishna et al., 2022) confirmed that CA benefits smallholder farmers in India, although technology targeting was needed for more significant impacts. They reported that while technology adoption was low among smallholder rice and wheat farmers (<2 ha of land), the on-farm effects of zero tillage on variable cost reduction (−7%) and yield (2%–15%) and profit improvement (+34%) was significant compared with non-adopters. Looking at a different region, Mosquera et al. (2019) examined the feasibility of CA practices for the Andes potato, forage, and grain systems. They found that crop productivity and net benefits (of the cost of production) of the CA system were increased by 25% and 24%, respectively, using the CA system compared with conventional practices. This study showed that CA increases and saves on production costs due to less tillage. While these studies cited above imply the cost advantages of CAMP over conventional farming, the results vary widely and are likely to be crop and site-specific.

5 | SOCIETAL ASPECTS

The societal aspects of transformative strategies, such as Conservation-AV, in agriculture are wide-ranging. These strategies can potentially reduce atmospheric carbon dioxide and other GHG emissions associated with agriculture, as well as enhance agricultural productivity. Integrating AV and other agricultural strategies can improve air quality, conserve biodiversity, reduce water pollution and soil erosion, and improve soil health (Islam & Reeder, 2014; Khosa et al., 2011; Stavi et al., 2012). Strategies such as CAMP, combined with agrivoltaic systems, can increase the resilience of renewable energy sources, and ensure sustainable food production in the long term. These strategies can also create economic opportunities in rural areas as well as provide environmental benefits and social benefits, such as greater food security, improved quality of life, and economic well-being (Gomiero, 2019). As illustrated in Table 2, there is a divergence between the social desirability of CAMP and its potential attractiveness to individual farmers; while many of the marginal costs associated with adopting CA accrue at the farm level, most of the benefits are captured by society. These societal benefits could be used as grounds for the development of regional, national, or global incentive programs supporting the adoption of CAMP. In the absence of such incentives, farmers' adoption of CAMP will remain a function of its perceived profitability at the individual farm scale (Knowler & Bradshaw, 2007).

TABLE 3 Summary of compelling research needed to evaluate the full potential of Conservation-agrivoltaics (Conservation-AV) in improving sustainability and food-energy production.

Research goals	Variables to evaluate	Method
Effect of Conservation-AV on yields of different crops	Photosynthesis, biomass production, and carbon fixation of the crops	Comparative field measurements in agrivoltaics system with and without CAMP implemented
Effect of Conservation-AV on resources availability of different crops	Solar radiation, water, and nutrient utilization, nitrogen-use efficiency	Comparative field measurements in agrivoltaics system with and without CAMP implemented
Effect of Conservation-AV on the water status of different crops	Plant water status (water potential), transpiration, stomatal conductance	Comparative field measurements in agrivoltaics system with and without CAMP implemented
Effect of Conservation-AV on local microclimates	Air temperature fluctuations, leaf temperatures, soil temperatures, and the water use efficiency of crops, soil moisture	Comparative field measurements in agrivoltaics system with and without CAMP implemented
Effect of Conservation-AV on soil structure and soil fertility	Runoff, soil erosion, nutrient losses, soil organic matter, soil properties, biodiversity, water availability for the crops, and microorganisms	Comparative field measurements in agrivoltaics system with and without CAMP implemented
Effect of Conservation-AV on mitigation of GHG emission	Soil carbon sequestration, greenhouse gas emissions	Comparative field measurements in agrivoltaics system with and without CAMP implemented
Economic aspects associated with Conservation-AV	Evaluation of cost of inputs needed for agricultural production, evaluation of distribution of benefits and costs	Comparative field measurements in agrivoltaics system with and without CAMP implemented
Effect of Conservation-AV on energy equivalent of different crops production	Output/input ratio, energy efficiency,	Comparative field measurements in agrivoltaics system with and without CAMP implemented
Effect of Conservation-AV on carbon footprint of different crops	Evaluation of C emissions derived directly from crop management practices, materials, and machinery inputs, coefficient of greenhouse gas emissions for each input	Comparative field measurements in agrivoltaics system with and without CAMP implemented

Abbreviation: CAMP, conservation agriculture management practices.

6 | CONCLUSIONS

The integration of CAMP into AV presents a promising avenue for addressing the pressing global challenges of climate change, food security, and sustainable land management. The combination of solar PV and food production on the same land through AV offers a unique opportunity to enhance energy and food security while minimizing land-use conflicts. However, the success of AV as a climate mitigation strategy hinges on the adoption of well-characterized CAMP strategies. While challenges and uncertainties remain, the potential benefits of CAMP in AV systems are substantial. These practices, including zero tillage, cover crops, crop rotation, and intercropping, have shown the potential to increase carbon storage, improve soil health, reduce GHG emissions, enhance biodiversity, and optimize resource use. Moreover, they hold promise for improving economic returns at both the individual and societal levels. Yet, the path to implementing CAMP in AV is not without obstacles. Economic considerations, particularly the divergence between social benefits and individual farm-level attractiveness, present challenges to widespread adoption. However, the societal benefits of reduced emissions, enhanced food security, and improved environmental quality could serve as a foundation for incentive programs and policy support. While research and data on CAMP in AV systems are still emerging, the need for further investigation is evident (Table 3). The integration of these practices paves not only the way for a more resilient and sustainable future but also underscores the importance of policymakers, farmers, researchers, and other stakeholders in realizing the full potential of AV with CAMP.

AUTHOR CONTRIBUTIONS

Alson Time and Wilgince Apollon planned the manuscript. Alson Time, Nuria Gomez-Casanovas, Paul Mwebaze, and Wilgince Apollon wrote the manuscript. Carl J Bernacchi, Evan H DeLucia, Nuria Gomez-Casanovas, Madhu Khanna, and Alson Time edited the manuscript.

ACKNOWLEDGMENTS

This work is funded by the SCAPES project funded by USDA-NIFA. Grant #2021-68012-35898. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the US Department of Agriculture. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture. USDA is an equal opportunity provider and employer.

The authors thank E. Peirce for the illustrations.

CONFLICT OF INTEREST STATEMENT

The author declares that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

All data used in this study is publicly available, and data sources are provided in the text.

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How to cite this article: Time, A., Gomez-Casanovas, N., Mwebaze, P., Apollon, W., Khanna, M., DeLucia, E. H., & Bernacchi, C. J. (2024). Conservation agrivoltaics for sustainable food-energy production. *Plants, People, Planet*, *6*(3), 558–569. https://doi.org/10.1002/ppp3.10481