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Synergies and trade-offs of multi-use solar landscapes

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Research on multi-use solar—combining solar energy with agriculture (agrivoltaics) or natural vegetation (ecovoltaics)—is developing rapidly, but interdisciplinary integration is needed to better address management issues and to guide future research. Agrivoltaics allows farmers to develop and manage microclimates, which can help to retain or expand agricultural production in the context of changing climate and land-water limitations. However, improvements in food–energy production and other co-benefits are often site-specific, depending on background climate, soil conditions and system design. To optimize multi-use systems, it is essential to consider local economic impacts, ecosystem services and stakeholder perspectives in design and implementation.

Commitment to mitigating climate change impacts by decarbonizing economies has resulted in the rapid deployment of new energy technologies that alter demands on resources, land use and economic models. Solar photovoltaics (PV) is one of the fastest-growing renewable energy technologies, offering the promise of affordable, sustainable energy[1]. Growing at a rate of 20–25% per year, the global capacity of PV to meet electricity demands could increase from 3.6% to 25% by 2050[2], which could eliminate 21% of emitted energy-related CO_2 (ref. 3). Recently, global installed PV capacity has grown exponentially from 39 GW in 2010 to 480 GW in 2018, 1,581 GW in 2023 and is expected to reach 8,519 GW by 2050[4]. This accelerated growth is driven by a combination of factors, including rapidly decreasing costs of PV system components and policy support at the local and global scale[4].

Future energy sector development and climate mitigation strategies will depend heavily on deploying solar PV systems[5]. However, solar PV requires extensive land area to meet utility-scale demand and shares site requirements similar to agriculture, which may cause competition with farmlands and vegetated spaces[6,7]. Without proper planning, the resulting land-cover change to solar PV can affect ecological function and agricultural productivity in some areas[8,9]. Indeed, socio-economic challenges emerge from prioritizing solar energy production over ecosystem services and revenues[10]. To address these challenges, approaches to co-locate PV facilities with crops, rangelands and/or native vegetation, and pollinators and ecological restoration on the same land—referred to as 'agrivoltaics', 'rangevoltaics' and 'ecovoltaics' (Fig. 1), respectively—are gaining traction as a strategy to maximize land-use efficiency and to minimize environmental impacts[9,11–14].

Research on these multi-use PV strategies is developing rapidly, but initial findings have yielded varied and disparate results on environmental and economic impacts, probably due to site-specific environmental conditions such as soil, geomorphology and climate, coupled with heterogeneity in the design, size, management and PV technology deployed[15]. This lack of clarity comes at a critical time in the energy transition when designers, developers, farmers and policymakers need reliable information integrating environmental, engineering, economic and political factors to develop and assess effective adoption and management strategies. This information needs to consider local conditions, avoiding overestimations of potential benefits and trade-offs as well as inappropriate and misleading generalizations. Therefore, this synthesis aims to (1) highlight the benefits and trade-offs of co-located systems from a land-use, environmental, social, technical and economic point of view (Supplementary Fig. 1); (2) investigate the potential for co-located systems to mitigate some of the main issues and challenges that solar PV can create, namely land use, environmental impacts, rural and urban community, and technical and economic performance; and (3) identify the knowledge gaps that need to be addressed to enable rapid deployment of co-located systems. First, we highlight the impacts of multi-use PV systems on food production and ecosystem services while supporting a transition to renewable energy. Using a data-driven approach, we summarize

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Fig. 1 | Agricultural land conversion and multi-use solar PV strategies. Top: conversion of agricultural land to solar PV installations. Bottom: examples of multi-use solar PV systems, including integration with native vegetation, pollinator habitats, grazing and crops. Photo credit: second photo from left in the bottom row, Chong Seok Choi.

findings from previous studies on co-located PV–agriculture systems across environmental, social, economic, technical and land-use disciplines. We then discuss the rationale for studying these systems, how they address environmental and technical challenges, and the socio-economic impacts and trade-offs in rural, off-grid and urban communities. Finally, we examine the design and technological advances in integrating PV systems with agriculture and conclude with a summary of future challenges and research priorities.

Land-use considerations for large-scale PV

Solar PV, despite having one of the highest power densities among all renewable energies ($5.8 \pm 1.2\ W.m^{-2}$)[16], is land-intensive (both spatially and temporally) compared with most non-renewable energy technologies[17] (Fig. 2a). Accounting for the energy consumption per unit area of countries[17], high-income countries such as the UK, Germany and Japan would need to utilize more than 40% of their total land area to meet their total primary energy needs entirely from solar. By contrast, some low- and middle-income countries in Asia would require more than their total land, while others in Africa and the Americas would need less than 5% of their total land (Fig. 2a). Although a relatively small fraction of the area is needed for large countries such as Canada, Australia, Brazil, Saudi Arabia and the USA, land-use requirements are not evenly distributed. For instance, most of the western, midwestern and southern states in the USA need around 10% of their land to meet total primary energy demands from solar, while other smaller states on the east coast would require more than 40% of their land (Supplementary Fig. 2). While it is instructive to compare the energy consumption per unit area of countries to the current energy density of solar PV, such estimates may overestimate land requirements, as ongoing improvements in PV technology efficiency could notably reduce the actual area needed. Furthermore, solar PV is expected to contribute only a portion of future renewable energy targets in most countries, and a substantial share of that contribution could come from rooftop installations with much higher power densities.

In addition to the local energy demands and population density, PV land-cover distributions may also vary based on the projected increase in energy consumption[18], land suitability and economic incentives[19]. Siting utility-scale PV is generally favoured on flat lands with high solar radiation that are accessible to existing grid networks and buffered from built environments[20]. Even though abandoned, marginal and degraded agricultural lands can be suitable sites[21], croplands are still favoured over other land covers to host PV installations[22]. In reflection, almost 60% of installed or planned PV installations have been already located on croplands, followed by grasslands, based on the previous land-cover class of land occupied by PV deployment[23] (Fig. 2b). Conversion of agricultural land to solar has created local concerns, even though the land area required to meet solar targets is only a small fraction of the total cropped area in the USA (less than 1%)[24].

Without proper planning and management, some larger-scale solar installations can contribute to localized habitat fragmentation and environmental degradation[9]. There also have been community concerns regarding ecological impacts, stormwater management[25], property value[25], changing landscape aesthetics[26] and whether direct benefits will be experienced locally[27]. Consequently, solar development can be potentially constrained, especially if developers fail to engage with the community, farmers and landowners[25]. At the same time, some agricultural areas are transitioning out of farming because of insufficient water resources for irrigation and rising temperatures. Abandoning cultivation can result in various environmental and socio-economic consequences including accelerated soil erosion[28], soil salinization[29] and a decline in farm income[30]. While there is a need to mitigate land abandonment and its negative impacts, another potential issue is agricultural expansion to replace these losses, support population growth or lifestyle changes[31], meet demands from globalization and progress in transport technology (that is, food distribution networks, supply chains or mechanization)[32], and compensate for the adoption of biofuel production[33].

Co-location of PV with other often competing land uses such as agriculture has emerged as a promising approach to address the environmental and societal challenges discussed above, including agricultural land transformation, climate change adaptation, energy accessibility, enhancing farm incomes and more sustainable

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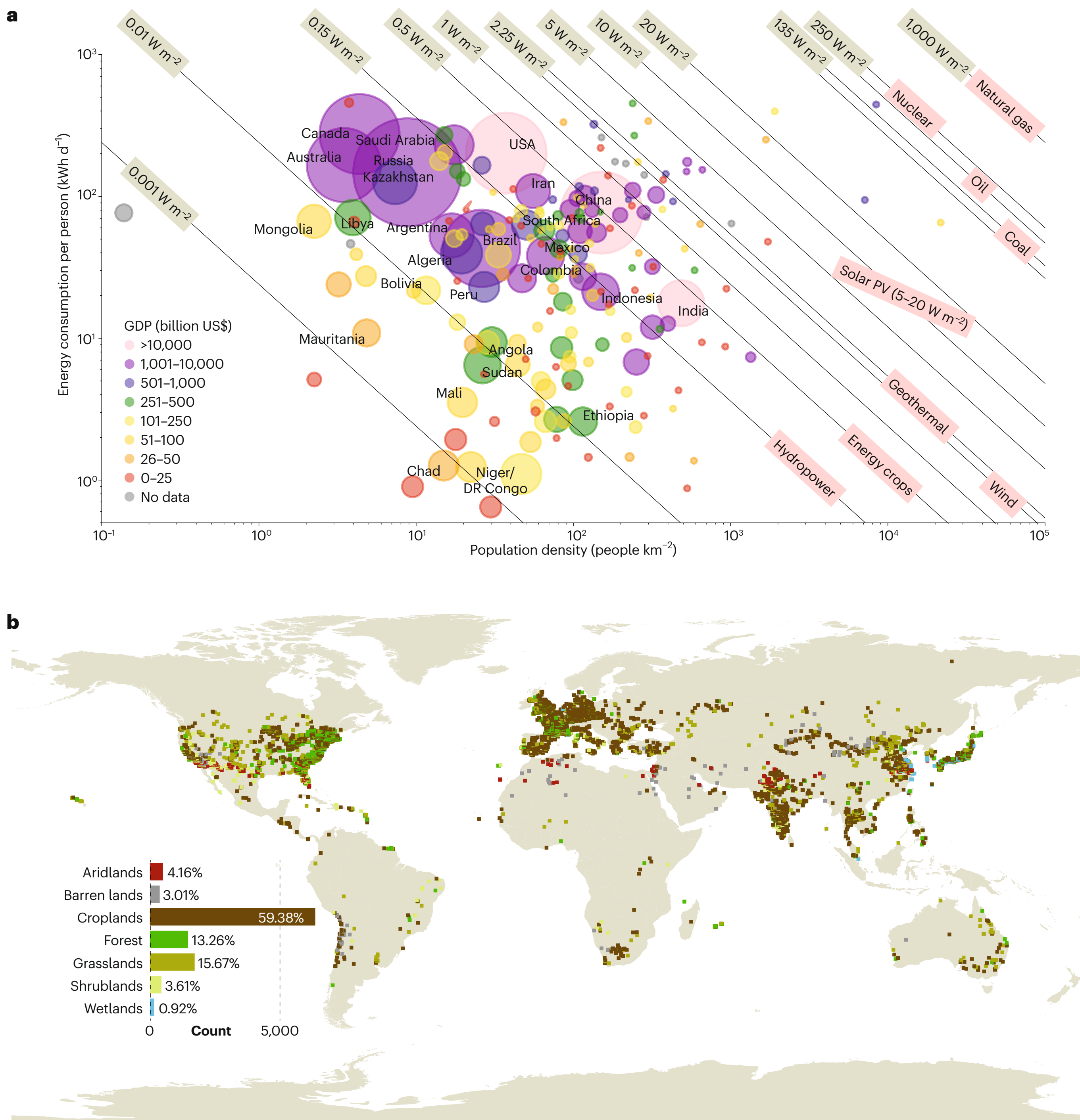

Fig. 2 | Scaling and mapping of PV land-use. a, Power consumption per person versus population density (most recent data) globally[17]. Point size is proportional to land area, except for areas less than 38,000 km^2 (for example, Belgium), which are shown by a fixed smallest point size to ensure visibility. The straight lines with slope −1 are contours of equal power consumption per unit area. GDP, gross domestic product. **b**, Prior land cover for PV sites. Land cover was obtained from the Copernicus Land Monitoring Service. Data were sensed and assessed using PROBA-V satellite observations, which are organized into millions of Sentinel-2 equivalent tiles of 110 × 110 km (ref. 145). The PV sites for 2021 were obtained from the Global Power Plant Database (http://datasets.wri.org/dataset/globalpowerplantdatabase)[146]. Figure adapted with permission from: **a**, ref. 17, Royal Society; **b**, ref. 23, Springer Nature Limited.

intensification of renewable energy generation[6,9,27,34–39]. Although this concept of dual or multi-land use has been successfully applied to other environmental attributes (for example, agroforestry, mixed cropping systems)[40], the concept of land sharing by PV and agriculture (or 'agrivoltaics') was first proposed in the 1980s[41] with minimal interest and need for application. Agrivoltaics has gained momentum in the past two decades, mostly driven by the rapid expansion of PV installations combined with growing interest from farmers, solar developers and environmental organizations[42].

Several pilot field and modelling studies have investigated the economic and environmental feasibility of co-location[9,11,13,35,43–46]. However, the rapid deployment of dual or multi-use solar PV is challenging partly due to the lack of comprehensive data from agrivoltaics projects of different scales from multiple agroclimatic regions of the

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world (Supplementary Fig. 3a). Moreover, currently almost 70% of the agrivoltaics pilot studies and agrivoltaics projects are deployed in arid climates, 90% of which are in high-income countries, where the potential for co-benefits on food security, climate change adaptation and environmental quality could be important (Supplementary Fig. 3b). However, this means that data are missing from other climates representing the full range of use cases, including from deployment in energy-intensive low- and middle-income nations with large carbon footprints and/or population densities, imbalanced food security, and scarcity of resources and technology. Addressing these challenges and knowledge gaps through comprehensive research is likely to benefit both PV development and land management decisions on a global scale.

Drivers of co-location scenarios

Agrivoltaics

Global food security and food system supply chains are increasingly affected by climate change[47], and the impacts will vary between climatic zones. Rising temperatures (Supplementary Fig. 4), changing rainfall frequency and intensity, and greater occurrence of some extreme events such as droughts, floods and heat stress can negatively impact crop production[48–50]. While some climate models may overestimate the impacts on crop yields[51] due to uncertainties in accounting for farmers' responses and adaptation strategies to extreme events, prolonged exposure to suboptimal temperatures during the growing season can adversely affect productivity. Therefore, information and strategies on new technologies and adaptation options could help farmers evaluate new approaches to minimize the negative impacts. Historical data of crop yields demonstrate that some adaptation measures improve or maintain crop yields in many regions of the world[52] (Supplementary Fig. 4). In this context, agrivoltaics is emerging as a promising adaptation strategy by providing an additional income stream[53] that can crucially support farmers to remain on their land (by modifying microclimates) and continue delivering essential agricultural services.

The capacity for plant photosynthesis (carbon fixation) is limited and reaches a maximum, light-saturated rate, after which photosynthesis is not affected by increasing light availability[54] (Fig. 3a). Under extreme heat and light availability, some plants even exhibit an inhibition in carbon fixation, resulting in yield loss[55]. In such conditions, shading produced by solar panels may benefit crop cultivation by reducing heat stress and excessive water loss[13,35] (Fig. 3b,c). Indeed, existing studies on agrivoltaics systems show that shading from solar panels can protect thermally stressed crops[56], particularly in regions where temperatures exceed 25 °C (ref. 57; Fig. 3c). By reducing the intensity of solar radiation incident on the leaves, shading has the potential to buffer temperature extremes, especially in hot and dry regions (Fig. 4a,b), resulting in lowering the temperature to close to the optimum leaf temperature and enhancing the photosynthetic rate[58] (Fig. 3b). While these PV systems provide shading during peak sun hours, other systems cause irregular radiation distribution such as vertical panels impeding plant growth[59]. Additionally, lower soil temperatures and wind speeds, facilitated by solar PV canopy over the crops, resulted in a reduction in crop evapotranspiration (Supplementary Notes) rates and consequent longer soil moisture retention (corresponding to an increase in water-use efficiency[45,60,61]; Fig. 4b,c). However, this improvement is less pronounced in areas where plant growth is already limited by lower irradiance and lower ambient air temperatures[13]. Nevertheless,

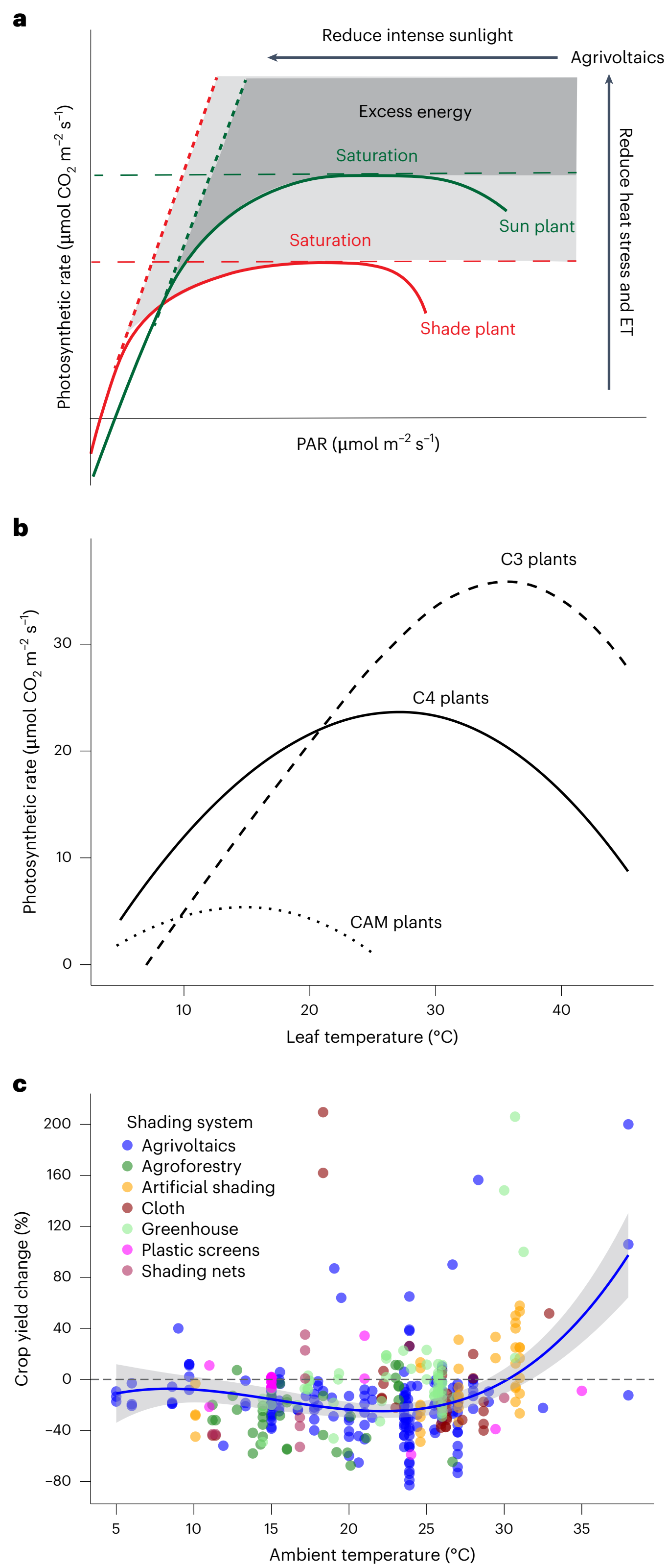

Fig. 3 | Impacts of light availability and temperature on photosynthesis and crop yield under different shading systems. a, Dependence of photosynthetic rate on available photosynthetic active radiation (PAR). PAR is the portion of the solar spectrum energy that is needed for photosynthesis; more in-depth explanation found in the Supplementary Notes. ET, evapotranspiration. **b**, The change of photosynthetic rate of C3, C4 and crassulacean acid metabolism (CAM) crops under the effect of temperature. Carbon dioxide is incorporated into a 3-carbon compound in C3 plants and a 4-carbon compound in C4 plants, and is stored in the form of an acid in CAM plants. **c**, Change of crop yield owing to different shading systems ($n = 367$) calculated as yield in (shading − full sun)/full sun. Negative values indicate lower yields in shading systems when compared with regions exposed to full sun conditions. Regression for agrivoltaics shading system is of degree 3 polynomial (crop yield change $= -16.9 + 42\,T + 179T^2 + 110.5T^3$, $R^2 = 0.22$, T = ambient temperature (°C), shading refers to 95% confidence interval). Panel **b** reproduced with permission from ref. 147, Springer Nature Limited.

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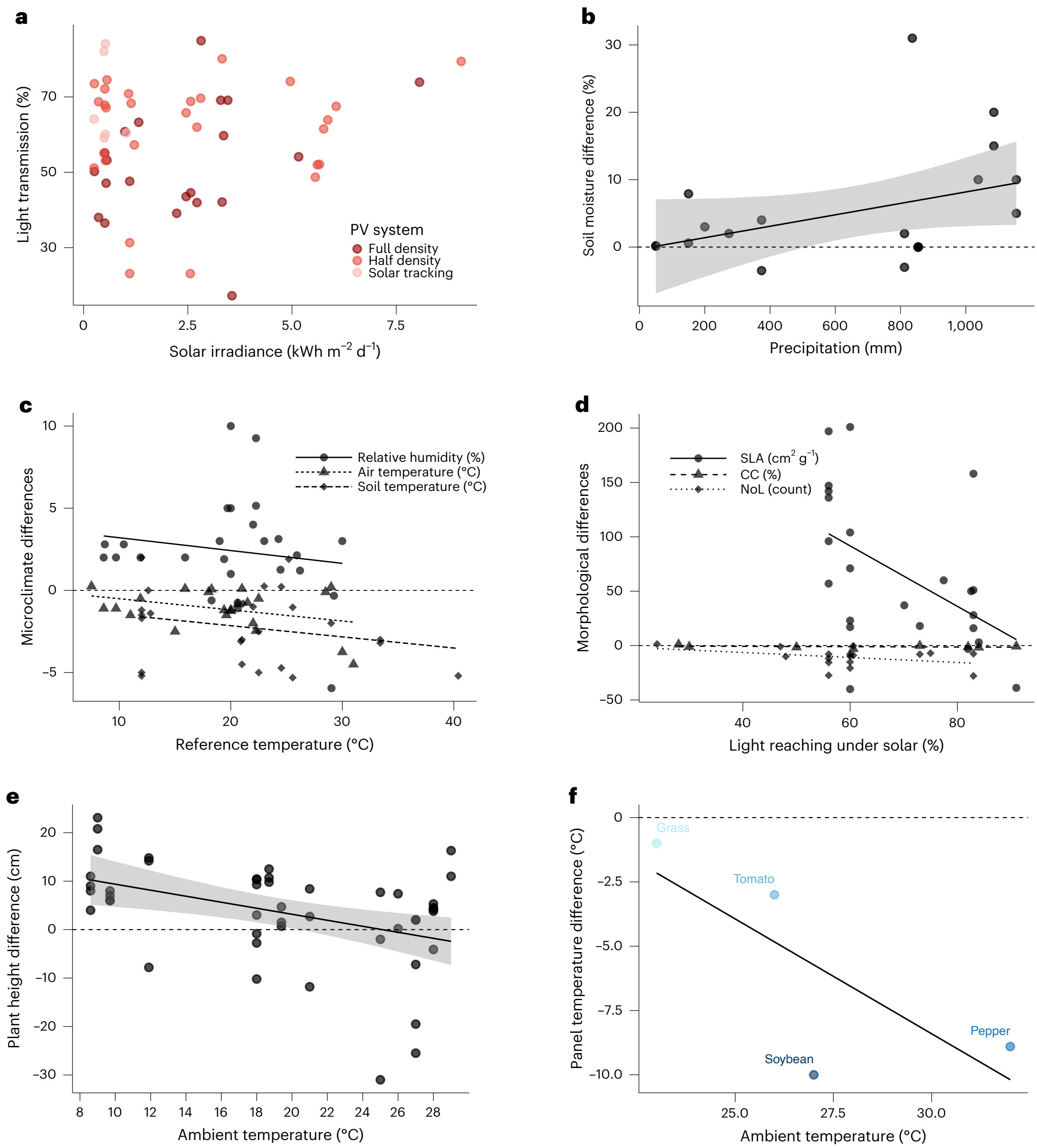

Fig. 4 | Environmental, morphological and technical changes within agrivoltaics systems where reductions are reported in negative values. a, Solar transmission is not correlated with the reference solar irradiance and the type of PV system due to changes in PV height, technology and spacings. **b**, Soil moisture content difference. Moisture under the panels is higher than in regions exposed to full sun conditions, while more moisture is retained with increased rainfall. Shading of the linear fitting refers to 95% confidence interval. **c**, Microclimate differences. Both air and soil temperatures are lower under the panels due to the higher relative humidity, while the cooling effect increases with the temperature. **d**, Morphological differences include specific leaf area (SLA), number of leaves (NoL) and chlorophyll content (CC). There are no significant changes ($P > 0.05$) in the chlorophyll content, but the number of leaves is lower under the panels, while the area of leaves is larger. With lower light and heat stresses, the plant concentrates its energy towards creating larger leaves instead of more leaves to optimize the surface area of light absorption. **e**, Plant height difference. Plants tend to be higher under panels in temperate climates to capture warmth from the sensible heat of panels and light radiated through interspaces. For hotter climates or periods, plants tend to be shorter to reduce the energy exchange of sensible heat from panels to plants. Shading of the linear fitting refers to 95% confidence interval. **f**, PV panel temperature differences. The cooling effect of crops on panels increases with heat intensification. More details on these changes can be found in previous work listed in the Supplementary References.

shade-induced morphological transformations (Fig. 4d,e), such as an increase in the leaf area and plant height to compensate for the light reduction, can be advantageous for many leafy vegetables, although further research is needed to assess the potential impacts of these altered microclimatic conditions on the nutritional value of crops[38,62,63].

The optimization of temperature and light within saturation limits as a result of shading potentially improves crop yields[22] and enhances the ability of some crops to expand beyond their current geographical and seasonal range, or to mitigate loss due to the impacts of climate change[36]. Furthermore, reducing evapotranspiration demand and heat stress through microclimate modifications can indirectly benefit agriculture by improving soil quality, enhancing microbial activity, and reducing salinization and soil erosion[10,16,36]. On the other hand, energy production, which is negatively correlated with high temperatures due

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to overheating, can be enhanced in agrivoltaic systems. In standalone systems, PV output reduction is observed experimentally for panel temperatures above 36 °C (ref. 64), while under real field conditions, reductions of 0.3% $°C^{-1}$ and 0.44% $°C^{-1}$ have been observed[65]. Underlying vegetation reduced the PV panel temperatures[66] owing to the cooling effect induced by the release of water during crop evapotranspiration[67] with substantial (up to 10 °C reduction) reductions in hot climates[35] (Fig. 4f).

Rangevoltaics

Grasslands, which comprise more than 30% of global land area, contribute to ecosystem services by storing about one-third of the global terrestrial carbon stocks[68] and support half of the global livestock capacity[69]. Over-exploitation of grazing lands in many regions of the world has resulted in the degradation of vegetation and accelerated soil erosion with negative impacts on food security, carbon sequestration (Fig. 5a) and environmental quality[70,71]. Similar to crops, the productivity of grassland is affected by recurrent droughts, temperature extremes and disturbances (for example, fires), which are predicted to be more frequent in the future[72]. Integrating PV on grasslands and rangelands may counterbalance the negative impacts of warming by restoring degraded lands[6] and improving biomass (pasture) production, especially under moderate shading. In fact, shading experiments have shown that high productivity can be achieved by common temperate rangeland plant species under light transmission rates comparable to those of solar installations[72] (Fig. 5b).

Photosynthesis, the natural mechanism for plant carbon intake, is sensitive to temperature up to an average threshold of 16 °C, above which the sequestration becomes affected by dryness[73]. Co-locating PV with native perennial grasses has the potential to improve soil carbon storage, pollinator supply, erosion resistance and water-holding capacity[74,75]. Vegetation reduces soil erosion caused by wind and water, and decreases dust emissions from disturbed soils through moisture retention and plant cover. This benefits both the soil and PV panels by minimizing the effect of wind eddies that carry fine particles to the surface of panels. The dust accumulation on panels has been reported to reduce output by 15–60% in both field and experimental sites due to dust-blocking the penetration of solar radiation into PV cells[76,77]. Furthermore, maintaining vegetation can reduce the water requirement (~0.02 m^3 MWh^{-1}) for panel cleaning and dust suppression from disturbed soil surfaces[78]. Any additional quantities of water used can benefit the vegetation growing under the panels, thus presenting a multifaceted solution that benefits both grassland ecosystems and solar energy production[6].

In addition to improving PV efficiency, managed grazing activities have the potential to restore degraded lands by increasing soil carbon levels and water-holding capacities[79]. Animals also promote biodiversity by spreading seeds from plants' diaspores with their wool using their hooves and faeces[80]. The dependency on livestock production has increased owing to the increase in meat[81] and milk[81] consumption, and a shift in consumer preference towards grasslands-pasture-based products[69]. Co-locating PV and grazing on grasslands, known as rangevoltaics or 'solar grazing', provides shading structures that serve as shelter areas for animals, protecting them from the summer heat, winds and intense storms. Rangevoltaics seems to be a viable mitigation strategy in some regions to support the requirement of Humane Farm Animal Care, which mandates the installation of a shading system in the case of temperatures consistently exceeding 22 °C (ref. 82). Results from existing rangevoltaics sites include reduced thermal stress, decreased animal water consumption and improved pasture productivity, particularly for small ruminants such as sheep and lambs (Fig. 5c). In comparison with non-co-location scenarios, pasture-based rabbits integrated with PV have been found to decrease emissions by 70%[83], even though higher initial investments were involved for the installation of additional fencing to prevent rabbit escape[84]. Nonetheless, the choice of ruminants was vital for PV compatibility; horses, goats and cows were not favoured as horses are 'fussy eaters', goats interrupted solar energy production by climbing on the panels and chewing the wires, and the size and height of the cows interfered with PV structure[85].

Ecovoltaics

Pollination, regarded as a critical ecosystem service for maintaining food, wild plants and biodiversity[86], is threatened by habitat fragmentation and alteration due to extensive anthropogenic land transformation for agriculture and energy production, often compounded by climatic changes (thermal stresses). Bees[87], butterflies[88] and vertebrate pollinator species[89] are already facing rapid rates of global extinction and are projected to decline further and shift their geographical distributions[90]. However, ecovoltaics approaches (co-location of PV and pollinators/ecological restoration), which co-prioritize energy production and ecosystem services during design and operational phases of utility-scale PV, can improve environment conditions for pollinator services, biodiversity conservation, restoration and ecosystem productivity[9,91]. In addition to the synergies provided from co-locating PV with native vegetation (as described in the 'Rangevoltaics' section; Fig. 5), PV arrays can increase soil moisture through shade protection, reduce the intensity of solar radiation, dampen high wind speeds and moderate soil and air temperature, especially in arid climates[9,91]. Underlying vegetation can mitigate soil moisture heterogeneity created by the interception and redistribution of precipitation by PV arrays, facilitating water transport to vegetated areas through root uptake and transpiration, which compensates for spatial differences in moisture levels[9]. These microclimatic modifications can also benefit pollinators in the landscape by reducing apparent climatic stress[92]. Floral blooming behaviour was enhanced at ecovoltaics sites (~460, 240 and 100 blooms per 100 m^2 in partial shade, full shade and full sun regions, respectively) due to the increased richness of pollinating insects. The cooler microclimate in shaded areas delays blooming times of forages, which remain in larger quantities compared with full sun, thus providing sustenance for pollinators during warmer periods[93]. Adopting ecovoltaics strategies near croplands and natural areas has shown promise[11], although research is still in its early stages.

Socio-economical assessment

Farmers constantly face economic challenges[94], income instabilities[95] and unexpected environmental threats[96], which are aggravated by increased demand for food, biofuel and livestock. The potential for additional and stable revenue from leasing land to solar developers could incentivize some farmers to abandon agriculture in favour of single-use PV[97]. While this strategy may seem more profitable than co-located systems due to higher densities of panels in standalone systems and the higher revenue per unit of land area, the risks of abandoning farming completely for farmers may prevent this from happening on a widespread scale. Farmer preferences could serve as a limiting factor for land conversion. From a socio-cultural perspective, farmers, who perceive agriculture as a way of life, have sought to negotiate solar lease terms to ensure a safe and smooth transition back to farming at the end of the solar project's lifespan (20–30 years), hoping to reclaim their arable lands[97]. While this may be acceptable in legal terms, soil quality degradation is a likely scenario without the presence of vegetation, resulting in additional costs to recover soil quality[74]. However, in scenarios where farmland is leased out for the lifetime of a solar project, appropriate co-location strategies, such as establishing native pollinator-friendly vegetation (or adopting ecovoltaics practices) combined with managed grazing, can improve soil quality and may even provide opportunities for biodiversity conservation and soil carbon sequestration[9]. On the other hand, farmers who are not planning on prioritizing agriculture after the end of the solar project could be constrained by regulatory and policy frameworks directed towards reducing farmland degradation, optimizing ecosystem services and

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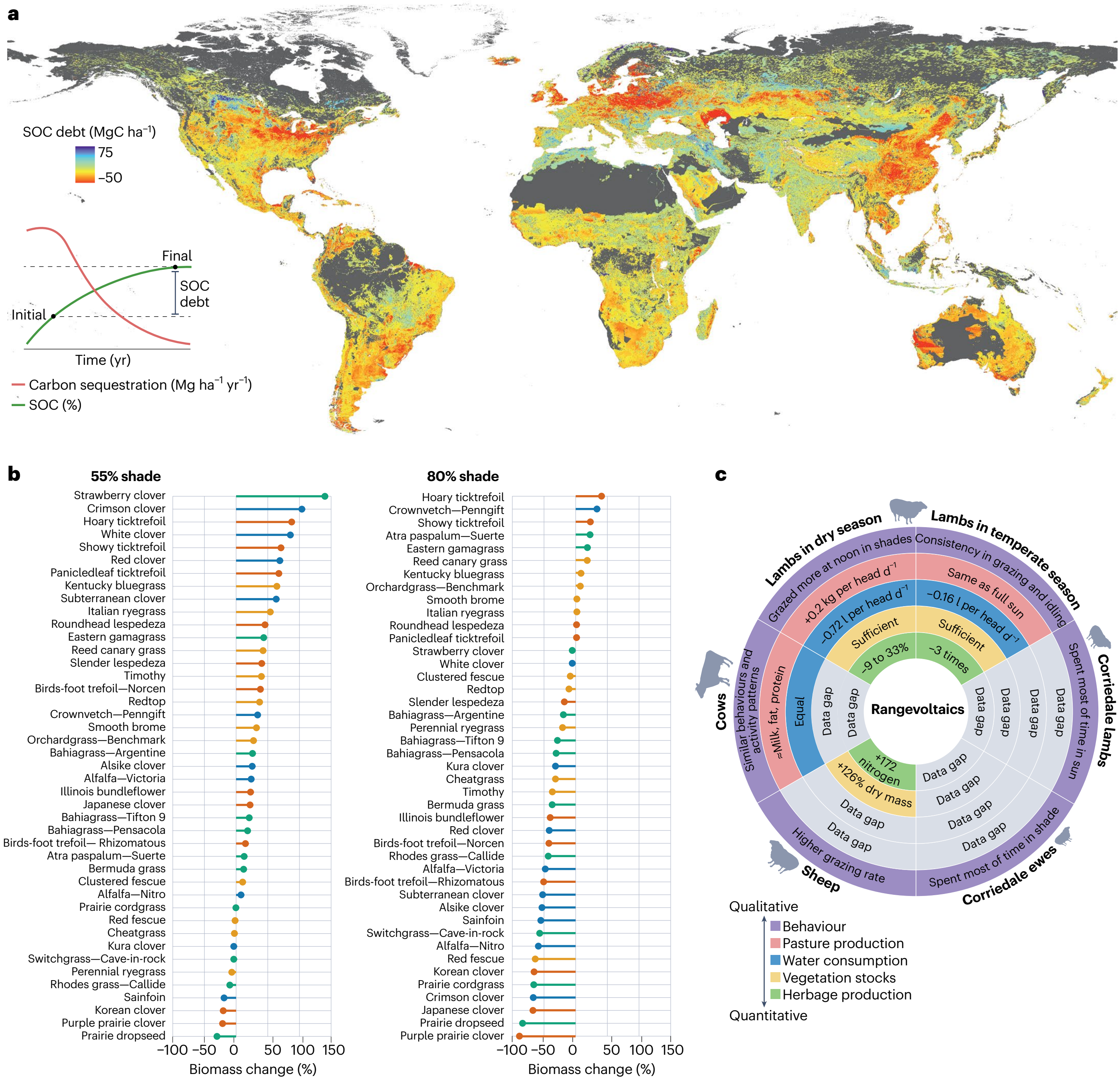

Fig. 5 | Effects of land use on soil carbon, biomass response to shade on biomass and rangevoltaics impact. a, Soil carbon debt in the top 2 m in which positive values (towards red colour) indicate loss and negative values (towards blue colour) depict net gains in soil organic carbon (SOC)[148]. Losses are mostly occurring in grasslands from the global spatial distribution of dominant land-cover classes[149]. **b**, Biomass change of grasses and forage crops due to 55% shade and 80% shade. Data obtained from ref. 150 **c**, Changes in animal behaviour and system productivity as a result of rangevoltaics, from previous research[151–155]. Panel **a** reproduced with permission from ref. 148, National Academy of Sciences.

enhancing land productivity. In fact, some countries have already established policies and zoning regulations to prevent agricultural land conversion to standalone PV systems[98,99], and others to improve co-located systems[100] mixed with financial incentives.

From an economic point of view, even with lower-density PV, co-located systems have the potential to substantially increase revenues from agricultural yields[101] (for example, ~15 times higher in the case of vineyard[102] and 10–22 times in the case of the rabbit-pasture system). Higher profits can also be earned from the increase in land value due to successful co-location, including improved yields (climate resilience from extended growing seasons and heat protection) and electricity generation[13,103,104]. In cases where yields are not improved, co-located systems could remain profitable by 48–53%[105]. Furthermore, co-location avoids terminating farming jobs, diversifies income to mitigate risks associated with reliance on any single source and provides supplemental power for farm activities during regional weather events[9,101]. In the case of ecovoltaics, future researchers should evaluate the profits that can be claimed indirectly—from maintaining or enhancing biodiversity, which has positive implications on agriculture by providing pollinator services—and directly—from producing high-value

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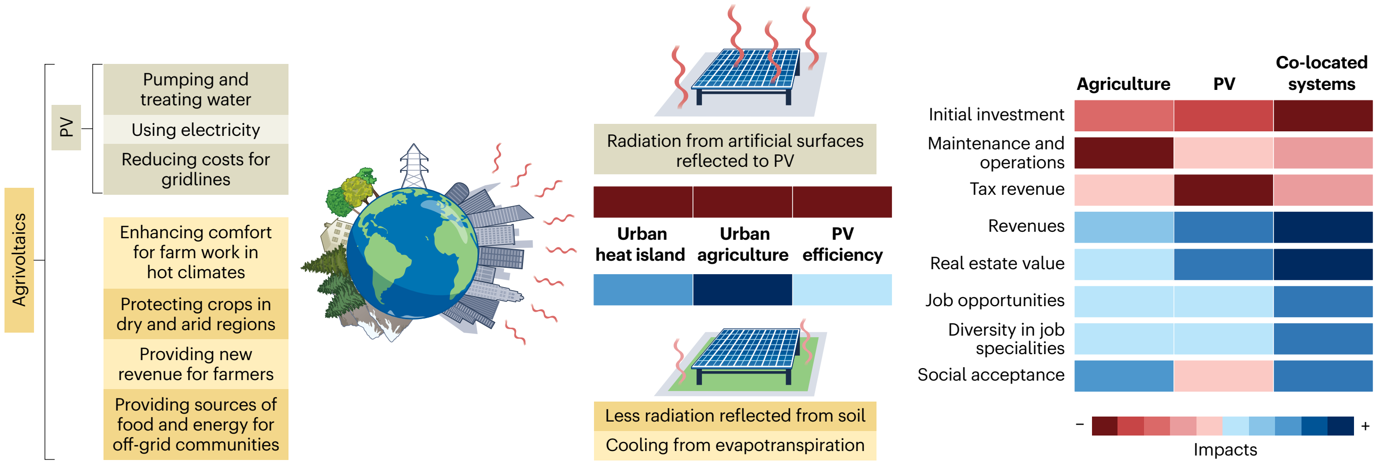

Fig. 6 | Socio-economic synergies in rural and urban areas. Left: the additional benefits that agrivoltaics systems can bring to standalone solar PV sites in rural systems. Middle: the main challenges that agrivoltaics unlike PV can mitigate in cities. Right: the potential of agrivoltaics to enhance the economic performance of both conventional farming and standalone solar PV systems.

wild medicinal plants. While both PV and co-located systems require initial investments, increased vegetation operation and maintenance costs in co-located systems[106] can be offset by additional revenue from irrigated water savings[45], agricultural yields[102], grazing-mediated vegetation management[84], pollinators' services[107] and reduction of panel cleaning activities from lower on-site dust emission rates[9]. Solar development also offers opportunities to expand agriculture to marginal lands[9,108], sloping terrain[109] or salinity-affected croplands[110], as solar installations are known to mitigate some of the challenges that render these areas unsuitable for crop production. Moreover, in hot climates and during extreme heat events, human labour under the shade of solar arrays can mitigate the risk of heat stress and fatigue, leading to increased labour productivity.

Economic incentives have a major role in elucidating the potential benefits and facilitating the social acceptance of co-located systems when compared with standalone PV systems[27,111]. Despite the need for coordination between farmers and developers, investors increasingly favour dual or multi-land-use strategies, especially when the costs of operations and maintenance can be covered by income from crop yields[83]. In fact, developers are often enthusiastic about working with and supporting farmers and local communities, viewing it as marketing to gain community acceptance; this is critical, as social–cultural aspects can influence the success of technology adoption within societies[112]. Notwithstanding, the land sharing between PV and crops is preferable to grasslands, especially when the aesthetics of natural landscapes are impacted by PV installations[113]. Therefore, policy and decision-makers would benefit by considering aesthetics while investing in lower-quality and/or marginal lands where changes from PV can be more environmentally beneficial. Yet, because agriculture is vital both economically and socio-culturally, many farmers may prefer to continue farming despite lower revenues. This highlights the need for strong policy frameworks and stakeholder involvement to ensure the long-term viability of both agriculture and energy production[114,115].

Rural and off-grid communities

Nearly 75% of people living in poverty live in rural areas and depend on agriculture for their livelihoods. Despite the high rate of migration from rural areas to urban centres, over half of the world's population currently lives in rural areas, highlighting opportunities to improve agricultural practices to enhance the quality of life[116]. In this regard, solar energy development can be designed as an integrated solution for rural farmers' issues, noting that opportunities and challenges of agrivoltaics may vary notably between high-income and low- and middle-income countries. Rural communities in low- and middle-income countries, particularly those with geographically isolated off-grid populations, small landholdings and limited capital, suffer from malnutrition, hunger and low income, have limited access to technology, services, markets and resources, and suffer from deficiencies in climate adaptation. These populations often lack access to electricity due to geographical isolation and affordability limitations[117]. Accordingly, crop-centric approaches—implementation of low-density PV over existing crops or processing facilities—are required to integrate renewable energy services into rural communities. These systems can help to meet the United Nations Sustainable Development Goals by alleviating poverty, reducing environmental degradation, providing affordable and clean energy[118] (Fig. 6), and supporting climate action[119]. Co-located systems could also provide shelters for crops and livestock from harsh weather conditions for people living in high-altitude regions and deserts. High capital expenditure and regulatory barriers might pose intractable challenges, especially because the costs of PV installations and associated benefits are competitive with other forms of energy supply[120]. However, although other renewable energy sources, such as geothermal and hydropower, are an option in some communities, their development faces challenges due to scalability issues, and often these resources are located in protected forest areas or far from demand centres[37]. Moreover, the co-location of PV and agriculture was found to be more profitable than diesel energy generation, even in the case of half-density PV[36]. These communities have low energy needs (Fig. 2a) and population densities, making crop-centric, decentralized, small-scale agrivoltaics systems more economically and environmentally friendly than diesel energy sources[121]. In these areas, agrivoltaics also provides a potential to grow high-value crops that would capture global market attention[6,36,101]. In addition to boosting investments, some crops (for example, aloe vera and agave) would require only manual handling and processing, thereby creating additional job opportunities[36].

In addition to the aforementioned co-benefits, agrivoltaics can address issues of rural communities in high-income countries that are concerned with financial sustainability[119]. In these remote communities, the option for large-scale utility PV systems is more viable, providing increased income stability[36,122,123] and more job opportunities in the case of land sharing, while profiting from the increased value of food sold in local communities during extreme weather events (when crops in full sun conditions cannot be grown)[124,125]. These opportunities help communities and their governments to benefit from retaining residents in agricultural areas, which usually face migration to urban centres. Therefore, strategies that stabilize rural economies and improve quality of life address this demanding regional and national challenge. Embracing these synergies, future research should focus on evaluating

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social behaviour changes, financial security and the effectiveness of marketing agrivoltaics, rangevoltaics or ecovoltaics products to rural communities. As such, recent studies have highlighted the importance of community engagement, targeted government initiatives, capacity building and long-term sustainability for successful agrivoltaics implementation in rural communities[119].

Urban communities

The transition from large-scale utility PV to integrating PV on rooftops and vacant areas in cities has been promoted[126] due to space limitations in urban areas. Modelling studies have shown that this approach can be sufficient in meeting energy demands (covering 15–35% area)[127]. However, the expansion of urban rooftop installations may exacerbate the heat island effect, leading to increased night-time temperatures and higher cooling demands[128]. Adding vegetation along with urban PV installations can decrease the panel temperature because of the cooling effect of evapotranspiration[67]. Urban agriculture can provide aesthetic, environmental, economic and social benefits. Local food production is shown to contribute to community economic development, support ecological preservation and biodiversity[129], boost mental health, balance elevated food prices, secure fresh and locally growing food[130], improve the quality of people's diets[131], create new job opportunities, and contribute to the reduction of heat and air pollution in the surrounding atmosphere[132]. Urban areas, where 68% of the world's population is projected to live by 2050[133], present a unique opportunity for agrivoltaics to improve food and energy security. Furthermore, urban agrivoltaics can mitigate well-known challenges in cities such as food deserts, excess heat, stormwater management and water shortages by enhancing microclimate boundaries[9,35,38,110], and energy poverty, grid failure and educational inequality by using urban agrivoltaics as decentralized energy systems[134].

Innovative technologies for co-located PV

Co-located PV systems have undergone continuous design modifications and upgrades to meet diverse requirements of agricultural and rangeland applications (Supplementary Fig. 5). Initially, PV structures for agrivoltaics systems were elevated to accommodate large machinery, animal movement and manual labour. Moreover, panel density was reduced by increasing panel spacings (that is, half-density) to allow more sunlight to reach the ground. Later, the concept of 'solar tracking' technology was applied, in which the panels track the sun's direction within a −50/+50° angle range to the horizontal, thereby maximizing the radiation absorption of panels and minimizing shading[104]. On the other hand, over four generations[135] the solar mirrors have transitioned from opaque to transparent, semi-transparent and bifacial panels. The increase in transparency has increased light transmission to the crops and energy absorption from the incident and diffused radiation on the panels' upward and downward faces. Optimizing transparency for panels not only involves adjusting the light intensity to optimize carbon intake and water usage, but also modifying the range of wavelengths captured for electricity conversion and those transmitted through the panel for crop growth[54,136]. For instance, semi-transparent solar cells increased absorption beyond 600 nm wavelengths while permitting the transmittance of blue (400–500 nm) and green (500–600 nm) light[137]. Optimal plant growth requires both blue and red light[136], which can be facilitated by spectral splitting such as the multi-coloured, semi-transparent organic solar cells. These cells have multi-colour built-in metallic structures to filter and transmit specific wavelength ranges[138]. To optimize agrivoltaics systems, future designs could prioritize transmitting both red and blue ranges in wavelengths to optimize photosynthesis beneath the panels and adsorb other wavelengths for electricity production while reducing the heat stress on plants. Another integrated solution is adding artificial lighting systems (that is, supplied by PV) for growing crops under the solar panels[139] (Supplementary Fig. 5). By contrast with greenhouse systems, agrivoltaics fuelled by light-emitting diodes can be applied on large-scale solar farms as naturally as possible without the need for resources to maintain a stable environment and stagnant microclimate conditions. PV layouts can also be adjusted to promote vertical farming underneath the solar panels to enhance land productivity and PV cooling in small-scale sites such as urban settings[140] (Supplementary Fig. 5). Future studies could focus on microclimate vertical gradients and assess the extent and type of crop production success at different elevations between the panels and the ground. Another applicable design is vertical (facades) solar PV panels that stand in the sun's direction in front of crops. However, such systems recorded higher temperatures owing to lower wind movements[141], which may be suitable for temperate and colder regions.

Future priorities and challenges

For co-located PV systems to address land productivity challenges, careful design and application of agrivoltaics systems can help to maximize benefits and minimize potential negative impacts and trade-offs, which are often site-specific. Hence, foundational data on suites of ecosystem services across multiple sites are important to determine which co-benefits should be targeted when siting utility-scale solar power plants on lands with varying scales, solar configurations and site management practices, and spanning multiple agroclimatic zones.

Despite the benefits of dual or multi-use solar landscapes on the environment, they can result in undesirable outcomes if implemented in areas with important environmental and ecological value. For example, converting a forest or a desert to a co-located PV system, converting lands that have already reached an optimum soil carbon storage and converting successful agricultural lands with optimum productivity into agrivoltaics can result in negative impacts[142,143]. In addition to issues related to topsoil disturbances and vegetation clearing during construction, co-located PV systems can also impact uniform vegetation establishment or crop production due to the uneven rainfall distribution[74,144]. Intense runoff from panels into interspaces can increase soil erosion in some systems and result in crop damage. While the intensity of rainwater distribution from the panels can be reduced in solar tracking systems that can be oriented horizontally during rain events, proper drainage for precipitation from the panels is still considered a better alternative to collecting rainwater and preserving it for later use. Another challenge is the reduction of light and temperature caused by the PV panels, which can buffer extreme heat events but might negatively impact plant growth during cooler or normal periods of the growing season. Integrating PV in agricultural lands in moderate climates can be detrimental to crop growth, while technologies to address unwanted light reduction can be expensive and hard to implement. Furthermore, marginal lands and arid regions can also be unsuitable for agrivoltaics, as additional investments are needed for irrigation and improving soil quality in some of these water- and nutrient-limited regions[9]. However, in these areas, high-value non-food crops (for example, agave and aloe) or biofuels that can usually tolerate high heat/sun exposure and marginal soils might be more suitable than traditional food crops[6].

As a rule of thumb, PV projects could be adopted in areas where ecosystem services can be improved or expanded. To minimize the loss of key soil functions, appropriate site preservation practices must be adopted to reduce topsoil disturbance during construction. After construction, it is essential to maintain vegetation immediately, as a longer gap between the initiation of the project and revegetation increases the risk of losing soil nutrients and degradation[9,74]. However, the challenge lies in designing a compatible and affordable system suitable for the maintenance of solar arrays and farming activities, such as using farm machinery and applying irrigation. The success of the project likely also depends on the crop suitability for co-location with solar infrastructure. This requires the evaluation of growth stature, light requirements, extent of mechanization, local acceptance, availability of processing facilities and marketing chains, and demand for products. Lastly, the

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main concern is that changes in the technical, environmental, social and economic aspects of co-located systems are in the early stages of investigation, highlighting the need for long-term studies. While regulatory and policy barriers may protect conservational lands, they can also restrict the emergence of small-scale grid-independent energy production that can provide food and energy security for off-grid, low-income and climate change and hazard-prone communities.

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Conceptualization: C.M., S.R., N.D. and J.M. Data curation: C.M. Methodology: C.M. and S.R. Formal analysis: C.M. Writing—original draft: C.M. and S.R. Writing—review and editing: C.M., S.R., J.M. and N.D. Supervision: S.R. Project administration: S.R. Funding acquisition: S.R. and J.M.

Competing interests

The authors declare no competing interests.

Additional information

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