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Designing solar farms for synergistic commercial and conservation outcomes

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ABSTRACT

Competition among land uses is making it increasingly difficult to set aside adequate space for wildlife and nature conservation, so it is imperative that opportunities that simultaneously achieve commercial and conservation outcomes be identified and seized. Such opportunities exist in the renewable energy industry. It is widely recognized that renewable energy generation benefits the ecosphere through reduced carbon emissions, but currently, further opportunities for realising direct and indirect conservation benefits through the design of solar farms are less well known. Among other opportunities, solar farm designs that deliver environmental credits through carbon sequestration and biodiversity improvements can deliver higher financial returns. Other opportunities to improve local hydrology, pollination, and pest-control services could be available depending on site-specific characteristics where solar farms are built, and the other land use practices that exist, or are possible, in the immediate vicinity. Here, we explore opportunities among renewable energy generation, agriculture, and conservation, through the co-location and innovative design of PV solar energy farms on grazing and croplands. These forms of land sharing can achieve higher land-equivalent ratios (LERs), a quantitative metric of the reduction in land use. We identify opportunities whereby solar farms can be designed to improve biodiversity, land condition, and conservation outcomes, while maintaining or increasing commercial returns. Much work remains, however, to understand the suite of opportunities available for achieving simultaneously the best commercial and conservation outcomes through solar farm designs in agricultural landscapes.

1. Introduction

Human population growth continues to exert increasing pressure on the land resources upon which we rely for diverse ecosystem services. Setting aside natural areas for wildlife and nature conservation, land sparing (Box 1; Fischer et al. 2008), has an important role in maintaining natural resources and the services they provide.

Given the often large and widely distributed areas required to conserve biodiversity, and the necessity of ensuring that such areas are properly managed and protection is enforced (Phalan et al., 2011), resources available for nature conservation are seldom sufficient. Consequently, approaches other than land sparing, to conserve biodiversity have gained more attention in recent years, especially in urban landscapes (Ives et al., 2016; Wolch et al., 2014). Urban green spaces, public parks and gardens, and green roofs and walls support increased biodiversity in patches across anthropogenic landscapes (Goddard et al., 2010). Further, many of these urban green spaces are multi-functional, supporting biodiversity, food production (e.g., public gardens and green roofs), and recreation (e.g., parks, golf courses). Such spaces can also provide additional benefits of improved air quality (Nowak et al., 2006), better physical and mental health (Ward Thompson et al., 2012; Wolch et al., 2014), and reduced heat-island effects (Tsilini et al., 2015). By leveraging these effects, urban designs can contribute to the achievement of the United Nations' Sustainability and Development Goals (United Nations, 2015). Beyond urban limits, the emergence of regenerative agriculture is another example of attempts to simultaneously achieve financial and conservation benefits. In such landscapes, the construction of solar farms presents an additional opportunity to co-design facilities that focus on achieving better commercial returns for agriculture and renewable energy businesses, while improving conservation outcomes. Here we examine the influence of spatial pairing of agricultural and solar assets, agrivoltaic systems (Dinesh and Pearce,

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2016; Dupraz et al., 2011a), on the achievement of simultaneous benefits across agriculture, industry, and conservation (Fig. 1; Semeraro et al. 2018).

2. Potential commercial and environmental returns from agrivoltaic systems

The opportunities presented by designing land sharing schemes that incorporate renewable energy production, agriculture, and nature conservation are just starting to be understood and, in a very limited number of cases, realised (Dupraz et al., 2011a; Hernandez et al., 2015; Kiesecker et al., 2011; Semeraro et al., 2018). Such opportunities should be vast given the very considerable land areas globally being committed to renewable energy generation (REN21, 2019; Trainor et al., 2016) and the extensive application of land to agriculture (e.g. 48.6 million km^2 [37.4% of global land area]; World Bank Group 2016). Indeed, the co-location of photovoltaic (PV) solar facilities within agricultural landscapes can increase productivity of crops under solar panels (Dupraz et al., 2011b; Marrou et al., 2013c), increase soil carbon, and reduce water evaporation (Armstrong et al., 2014; Hassanpour Adeh et al., 2018; Marrou et al., 2013a).

Achieving better commercial and environmental outcomes from solar farms will ultimately depend on the design of hybrid land-use systems that capitalize on the opportunities presented at individual locations. These designs, in turn, will need to be underpinned by a detailed understanding of local conditions and opportunities. In general, though, solar farms constructed on degraded land should enable vegetation and soil carbon to regenerate, and at least some local biodiversity to re-establish in areas from which it had previously been lost (Montag et al., 2016; Parker and McQueen, 2013). Accordingly, gains at multiple levels should be achievable, beyond that which might be achieved by solar power installation designs that do not explicitly consider such design options. For example, combining cropping or other agricultural production with solar farms, on the same land, reduces the space required for both uses, if sited separately. By using degraded landscapes (e.g., low productivity croplands, or nutrient-poor, overgrazed livestock properties) for the installation of solar farms, native communities of plant and animal species may be enhanced, and if coupled with regenerative agriculture, much greater synergies might be achieved.

While achieving coupled economic and environmental outcomes in agrivoltaic systems is laudable, our current understanding of the many interacting factors that would affect solar electricity production and the simultaneous generation of positive environmental and biodiversity outcomes is extremely limited. The generation of additional knowledge of these opportunities is urgent, especially in light of the current and rapidly increasing extent of solar farms. Without such understanding, our ability to limit the impacts of solar farms, much less realise opportunities associated with optimal hybrid designs, is likely to be missed. Our purpose here, therefore, is to explore opportunities that might exist for designing agrivoltaic systems and determine what information is required to make robust choices among designs.

3. Understanding the potential benefits and limitations of agrivoltaic systems

3.1. PV solar farm performance

Solar farms require ongoing maintenance. This maintenance can include keeping the solar panels free of debris (e.g., dust, leaves, bird droppings), which can reduce panel efficiency by up to 7% over extended periods without rain or panel cleaning (Goossens and Van Kerschaever, 1999; Jaszczur et al., 2019; Mejia et al., 2014). Therefore, panels need cleaning periodically to maintain high levels of energy production (Fig. 2a; Mani and Pillai 2010; Lovich and Ennen 2011).

Dust accumulation on panels is a major issue for solar farms in arid areas, especially those without vegetation or ground cover to trap dust or reduce local wind speeds. Arid lands also tend to be areas with large solar resources, suggesting that maintenance will be an important consideration for solar farms in many locations. Dust accumulation can be reduced by adding vegetation to solar farms (Li et al., 2007; Munson et al., 2011). In addition, large-scale PV solar farms increase local ambient temperatures and act as heat-islands (Armstrong et al., 2016; Barron-Gafford et al., 2016; Edalat, 2017; Zhang and Xu, 2020) which can reduce the efficiency and performance of solar panels (Fesharaki et al., 2011; Kande et al., 2016; Popovici et al., 2016) and have negative impacts on plants and wildlife (Yow, 2007). Vegetation cover around and under solar panels can reduce this heat-island effect and help maintain solar panel efficiency (Kande et al., 2016; Tsilini et al., 2015). For example, vegetative ground cover can reduce degradation of solar panel backsheets (the protective layer on the backside of the solar panel). Backsheets protect the internal electrical components from weathering and act as insolation for the solar panel (Gambogi et al., 2013; Oreski and Wallner, 2005; Voronko et al., 2015). Like many polymetric materials, backsheets are subject to degradation through environmental stressors, such as temperature, humidity, and ultraviolet light (Lin et al., 2016; Oreski and Wallner, 2005). Grass and vegetative cover under solar panels can reduce the damaging effects of UV light on the backsheets and slow their degradation (Fairbrother et al., 2018). Consequently, incorporating vegetation buffers between sets of solar panels or around the installation's perimeter, or both, may produce multiple benefits, including reduced dust accumulation, reduced operating temperatures of PV panels, and provide habitat for pollinators and other wildlife (Semeraro et al., 2018).

In contrast to the advantages of incorporating vegetation in solar farm designs, shading from vegetation will reduce energy output from PV panels. Therefore, solar panels need to remain un-shaded as much as

Box 1
Glossary of terms.

Term.	Definition.	Ref.
Agrivoltaic system.	Co-located agriculture; (crops or livestock) and energy production on the same land area.	Dupraz et al. 2011a; Dinesh and Pearce 2016.
Land equivalent ratio.	The relative land area required by monocultures to produce the same yields as intercropping[1.]	Mead and Willey 1980.
Regenerative agriculture.	Farming practices that rehabilitate agricultural land (e.g. soil biodiversity, carbon, health, and organic matter) to enhance production.	Rodale Institute 2014.
Land sharing.	Biodiversity conservation and food production occurring on the same land (aka wildlife-friendly farming)	Green et al. 2005; Fischer et al. 2008; Phalan et al. 2011.
Land sparing.	Land designated for conservation use separate for all other uses.	Green et al. 2005; Fischer et al. 2008; Phalan et al. 2011.

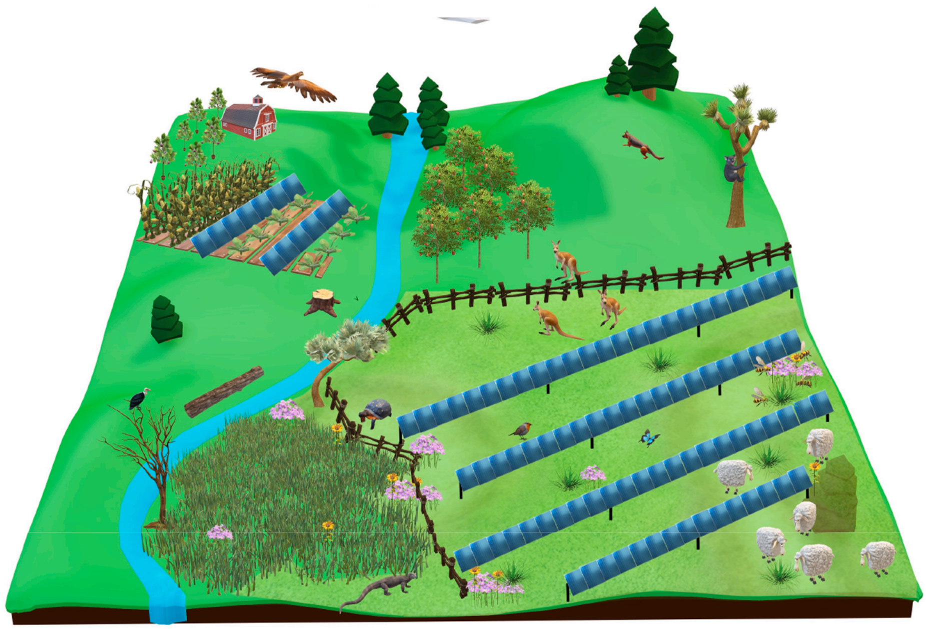

Fig. 1. A hypothetical agrivoltaic system in Australia. Solar panels are co-located within croplands and on existing grazing land.

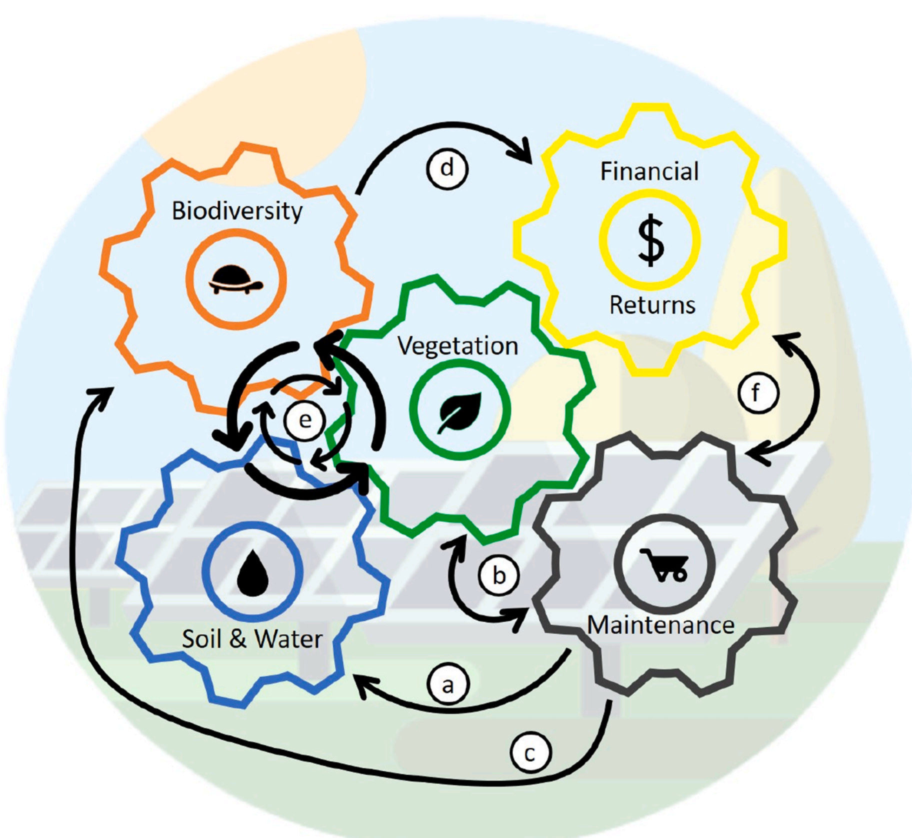

Fig. 2. Conceptual model of components and interactions that influence land condition in agrivoltaic systems. Five major components are summarized through their interactions (represented by a – f and described in the text) by: Biodiversity (wildlife habitat, species diversity, refugia and cover, pollinator and predators, and ecosystem services); Soil and Water (run-off, erosion, soil moisture, soil compaction, dust accumulation, nutrients, fertilizers); Vegetation (ground cover, vegetation complexity, weeds, food production); Maintenance (clearing, infrastructure, mowing, herbicide use, pesticide use, livestock health, cultivation and harvest); Financial returns (carbon credits, electricity production, jobs, site maintenance, pest control, profit through livestock/crop yields, supplemental feeding for livestock).

possible to retain efficient energy production, which often requires vegetation management (Fig. 2b). Tall grasses require periodic mowing, spraying with herbicides, or grazing by livestock. Both periodic mowing and chemical suppression require staff and equipment whose costs reduce the financial returns of solar farms (Fig. 2b, e). Chemical suppression also comes with added negative effects of chemicals leaching into the environment and potential costs of preventing and mitigating their effects (Abbasi and Abbasi, 2000; Montag et al., 2016) and potential biodiversity impacts in the vicinity (e.g., Roundup™; Relyea 2005). In contrast, using livestock to manage vegetation can provide mutual benefits to solar farm owners via vegetation management and agricultural production through forage for livestock (Montag et al., 2016; Sinha et al., 2018). The utility of such approaches with respect to maximising financial returns will depend on how the PV panels are mounted, and the type of livestock used for vegetation management. For instance, the combination of low panels and large or climbing livestock may lead to solar panel damage. Therefore, panel design, vegetation choices, and stocking approaches all need to be integral to the design of agrivoltaic systems. Through such design considerations, solar farms have the potential to increase their financial returns by using grazing livestock for vegetation management to suppress vegetation from over-shading solar panels. Further, in some systems, native herbivores could be encouraged to occupy and forage within solar facilities, (e.g., kangaroos or wallabies in Australia, pronghorn antelope in the USA), providing biodiversity benefits, as well as low-cost vegetation management that may also, in some cases, provide additional income through biodiversity offsets (Fig. 2c, d).

3.2. Agriculture and crops

Solar farms can occupy large areas of land, and thereby compete with other agricultural uses, such as grazing and croplands. But, agrivoltaic systems that couple PV power generation with shade-tolerant crops can increase returns up to 30% in some cases, compared to producing energy and crops separately (Dinesh and Pearce, 2016). Further, agrivoltaic systems can be highly productive and increase overall land productivity by 60–70% (Dupraz et al., 2011a) as quantified by land-equivalent ratios (LERs, Box 1; Mead and Willey 1980). Agrivoltaic systems have achieved LER = 1.7, (i.e., a 100 ha. agrivoltaic farm produces as much energy and crop yields as two separate farms totalling 170 ha.; Dupraz et al. 2011a). While not all crops are suitable for agrivoltaic systems, lettuce, sweet potato, alfalfa, and plants with high photosynthetic rates and low root density or high shade tolerance can grow well in association with solar farms (Dinesh and Pearce, 2016; Dupraz et al., 2011b; Ezzaeri et al., 2018; Marrou et al., 2013c; Seidlova et al., 2009; Valle et al., 2017). In these hybrid systems, shading from solar panels helps maintain soil moisture and water retention in under-panel vegetation and crops (Hassanpour Adeh et al., 2018). For example, increased water retention led to an increase in fresh harvest weight of cucumbers and lettuce grown under solar panels (Marrou et al., 2013a). Given the diversity of potential crops and their varying requirements (e.g., photosynthetic, soil, water, etc.), not all crop species will be suitable in agrivoltaic systems. Onions grown under solar panels in Wales produced reduced fresh and dry matter harvest weights compared to non-solar farm yields (Kadowaki et al., 2012). These effects were also seasonally dependent; shade from solar panels was more detrimental in winter than summer (Dupraz et al., 2011b). Clearly, given the diversity of local environmental conditions among sites, and trait diversity among crop plants, experimentation will be required to learn which combinations work best for each region and set of conditions.

3.3. Biodiversity

In addition to producing energy and agricultural products, agrivoltaic facilities can benefit biodiversity. PV solar farms can act as artificial habitat islands by providing shelter that may otherwise have been diminished or destroyed in degraded environments (Sinha et al., 2018). Similar to artificial reefs in lakes and oceans (Baine, 2001; Bohnsack and Sutherland, 1985; Creque et al., 2006; Folpp et al., 2020), solar farms add structural complexity and increased heterogeneity to microhabitats at multiple levels. Solar panels add physical structure to the environment that provides microhabitats, adding shelter and refugia for wildlife (Sinha et al., 2018). Multiple studies in Europe have shown that solar farms support more biodiversity (bumblebees, butterflies, and plant species) than control sites (arable fields; Parker and McQueen 2013; Montag et al. 2016). The increased structural complexity provided by solar panels provide nesting and perch sites for many birds (Beatty et al., 2017; DeVault et al., 2014; Peschel, 2010) including ground nesting birds, which also likely benefit from added protection from aerial predators. Solar farm boundary fences may also provide additional protection for prey species residing within solar farms, as some terrestrial predators may be deterred by facility boundary fences (Sinha et al., 2018).

During the construction phase of PV solar projects, wildlife is often displaced (Hernandez et al., 2014; Lovich and Ennen, 2011; Turney and Fthenakis, 2011), but if managed well, wildlife will repopulate sites following construction (Peschel, 2010). While there are reports of wildlife mortality at solar installations (i.e., bird collisions; Walston et al. 2016; Visser et al. 2019; feather damage and insect incineration from concentrated solar-thermal (CST) solar facilities (McCrary et al. 1984; Kagan et al. 2014; ecological traps; Horváth et al. 2010; Kagan et al. 2014), the mortality associated with PV solar farms is thought to be much less than that of traditional power facilities (Walston et al., 2016).

Solar panels can also reduce the mean ground temperatures below them, and increase local thermal heterogeneity. Similarly, mean moisture and moisture heterogeneity can increase where solar panels are installed. These local effects are generated by the sun-shade mosaics caused by panels, and benefit many plant and animal species (Beatty et al., 2017; Hassanpour Adeh et al., 2018). Vegetation that grows under and around solar panels produces shelter, nesting material, and forage for many species (Montag et al. 2016; Beatty et al. 2017; Fig. 2e). In addition, shading by solar panels can cool surface temperatures and increase soil moisture compared to open landscapes (Hassanpour Adeh et al., 2018; Marrou et al., 2013b). Solar farms that host more vegetation than would otherwise be there will also provide habitat for wildlife to recolonize. Sites with greater botanical diversity also support greater invertebrate diversity, including pollinators that provide important ecosystem services (Montag et al., 2016; Semeraro et al., 2018; Vanbergen et al., 2013; Walston et al., 2018). Wildlife and vegetation on solar farms interact positively; establishing diverse vegetation communities will encourage biodiversity including pollinators and predators, which, in turn, will promote more botanical diversity. Improving land condition on solar farms by establishing vegetative cover, including native grasses, shrubs, and flowering plants, improves soil health through increased soil carbon, water retention and infiltration, and reduced surface run-off and consequent erosion (Bartley et al., 2014; Li et al., 2007). Hydrodynamics, whereby water penetration into the soil is greater because the presence of plants can help recharge water tables, and reduce evaporative water losses (Yapp et al., 2010).

Although the design of solar farms can promote better environmental outcomes, some negative effects of PV installations on ecological communities have been identified. Most investigations of these negative effects have focused on volant fauna. Birds and bats can be injured or killed if they collide with solar panels and related infrastructure (Visser et al., 2019; Walston et al., 2016). Because solar panels reflect horizontal polarized light, similar to water bodies, they can also attract flying aquatic insects in search of suitable egg-laying locations (Horváth et al., 2010). This ‘lake-effect’ could also cause birds to collide with solar panels, however, this effect has not been thoroughly investigated, and there are few studies to support or refute this ‘lake-effect’ in birds (Kagan et al., 2014; Visser et al., 2019). While solar farms can negatively impact wildlife, avian mortality due to utility-scale solar facilities are considerably lower than the mortality associated with other anthropogenic causes, including building collisions, road mortality, and habitat loss associated with fossil fuel development (Walston et al., 2016). Where such potential concerns are realised, there will be opportunities to mitigate these, through strategic site planning and design.

3.4. Design and placement of solar farms

The installation of solar farms can disturb landscapes through large-scale clearing and site preparation. The construction of any solar farm will cause some level of disturbance to natural habitats. The net benefits of building a new farm will depend on at least two factors: the original quality of the land prior to its current use, and its current state. For example, high-quality habitats that have been degraded in recent years through intense cropping, overgrazing, or other damaging agricultural or industrial practices have the most to gain from regenerative approaches available to agrivoltaic systems. Regenerative agriculture coupled with PV solar capacity can help improve the economic profitability, environmental, and ecological values of a site. Degraded landscapes of historical high-quality that are selected for regenerative agrivoltaic sites have the potential to experience the lowest relative degradation and benefit most over the long term, given their current poor land condition. Of course, many agricultural properties are well managed and not degraded. In these cases, landowners may be able to improve low productivity areas (perhaps with poor soil nutrients, rocky or undulating land, etc.) through land sparing patches or co-planting alongside solar panels.

Generally, the design and potential outcomes from agrivoltaic installations will be site specific. For example, landscapes that support burrowing species, such as desert tortoises (*Gopherus agassizii)* or burrowing owls (*Athene cunicularia*), may be adversely affected if burrows are collapsed by machinery during solar farm construction (Gibson et al., 2017; Lovich and Ennen, 2011). Ideally, such negative impacts could be minimised by using existing low-quality habitats and or low productivity agricultural areas or improving solar farm design and construction.

Many factors determine the suitability of sites for PV solar farms, including the quality of the solar resource (Hernandez et al., 2014; Lovich and Ennen, 2011; Moore-O'Leary et al., 2017), available grid connections, costs of construction, and various environmental considerations. These considerations are even greater for agrivoltaic systems. For example, solar facilities may require perimeter fences for security, but fences can block wildlife movement into or across solar farms. Site designs can mitigate these negative effects on wildlife to some extent through the application of wildlife-friendly fencing, wildlife gates, or travel corridors (Cypher et al., 2019). Which mitigants are most effective will depend on the wildlife communities in the local area. Some wildlife species may be beneficial to solar farms. For example, native herbivores (e.g., rabbits, kangaroos) may contribute to grass and vegetation suppression. Perimeter fences around PV installations may also block migratory routes or access to streams or ephemeral wetlands located within solar farms. Site managers may also require access to water for periodic cleaning of solar panels to reduce dust accumulation, especially in arid landscapes, or where birds are plentiful, and solar panel efficiency is reduced by fouling (Jaszczur et al., 2019; Lovich and Ennen, 2011; Mani and Pillai, 2010). Local water resources used for panel cleaning are at least returned to the local environment, where it may be used by plants and animals. Where water is very limited, its use by solar farms may impact other environmental uses, such as access to free water by wildlife (Cameron et al., 2012; Grippo et al., 2014).

4. Research priorities and recommendations

Typically, solar farms are designed and managed only to produce renewable electricity. Therefore, it is reasonable that solar farm developers target locations with the highest quality solar resources that can easily be connected to electricity grids or local loads. There are, however, greater financial returns possible by coupling solar farm returns with agricultural production and environmental restoration and conservation. Agricultural markets are well developed and understood, and can easily be modelled in combination with power production to create agrivoltic designs that generate greater returns. Environmental markets for carbon and biodiversity credits and natural capital are much less well known, and are changing rapidly. Currently, carbon credits, perhaps the best known of these markets, vary by more than an order of magnitude in price, and it is reasonable to assume the value of these credits will increase substantially as more carbon reduction targets are legislated, and the demand from the voluntary market continues to expand. Moreover, the opportunity for land holders to access debt and equity to support their businesses by leveraging their natural capital is only just starting to emerge as a financial instrument. Clearly, much more research will be required to understand and capture these emerging market opportunities.

These additional returns can be realised not just by accessing these additional revenue streams, but also realising available synergies among different land uses in close proximity. For example, appropriate ground cover under, and in the vicinity of, solar panels could lower running costs for solar facilities, while producing carbon and other environmental credits, such as access to run-off mediation funds, while providing pollination and pest control services to adjacent horticultural production (Delaney et al., 2020; Li and Waller, 2015). Consequently, rather than simply focusing only on existing priorities, such as optimizing the design, placement, and maintenance of solar facilities (Peschel, 2010; Sinha et al., 2018), considerable opportunities exist to consider how landscapes can be improved, rehabilitated, or both, through the production of multiple products from a mosaic of land uses in more sustainable ways. These opportunities exist in a variety of combinations that could include energy production, shade-tolerant crops, feed for livestock, and wildlife refuge, among others.

While the potential to apply such design principles for simultaneous and improved conservation, sustainability, and commercial returns clearly exist, understanding how to design for such synergistic outcomes is in its infancy. Better understanding of these opportunities will arise from research directed to address specific questions regarding how to determine the most appropriate mix of scales and patterns of deployment of various land uses. The opportunities for co-design will be complex and location-specific, depending on a combination of ambient environmental conditions, the agricultural land uses possible and practiced at that location, the regulatory frameworks under which such a facility will operate in terms of the environmental costs and credits available, and the types of technology deployed. Decision support tools will also need to be developed to optimize these choices in different circumstances. We suggest that future solar projects should initially explore multiple use of their sites to achieve better environmental and commercial outcomes. In its simplest form, an agrivoltaic system might support both energy production and under-panel crop production. Such a design would reduce the land required for both uses (i.e. increase the LER) while supporting at least some biodiversity. Alternatively, an agrivoltaic system that uses livestock for vegetation management could reduce labour costs for staff to mow or spray vegetation, support local graziers via leasing solar farmland to feed stock, and will incidentally provide habitat for plant and animal diversity. These co-benefits may be further increased by incorporating inter-panel vegetation buffers, tree and shrub buffers around solar facilities, especially in mosaics of other land use systems. As our knowledge of the opportunities in this space increase, agrivoltaic solar facilities have the potential to contribute to the rehabilitation, and possibly improvement, of biodiversity on degraded landscapes of poor ecological and economic value and increase the economic returns to solar farms and agriculture while improving land condition and conservation outcomes.

Rather than constructing new facilities on undisturbed native vegetation, or green-field sites, even areas of low biodiversity value, developers could focus instead on reusing degraded landscapes for solar farm development (Cameron et al., 2012; Milbrandt et al., 2014). Degraded landscapes, overgrazed land, low productivity croplands, and sites disturbed by anthropogenic practices, are plentiful, and many could potentially be repurposed. These degraded landscapes are generally under-used, have poor yield potential, are difficult to cultivate, or have low economic value that make them comparatively inexpensive to acquire. However, some regions may be constrained by access and proximity to electricity grid connections and access roads for construction. Alternatively, site selection for solar energy projects may raise local real-estate prices with the promise of better access to grid power in the vicinity solar farms installations, thereby increasing property values, or commercial development potential.

The reuse of degraded or lower quality agricultural land, already modified from its original state, provides an opportunity to rehabilitate or improve land in support of better agrivoltaic system revenues and improved biodiversity (Hernandez et al., 2016; Kiesecker et al., 2011). Such modification of existing landscapes into agricultural, environmental, and energy generating mosaics will undoubtably produce trade-offs whereby one use of the space is compromised in favour of another. Such trade-offs should be reduced to some extent through careful design and management that minimizes negative effects and enhances the positive ones (Neilly et al., 2018).

PV solar farm facilities have generally conformed to standard designs, with panels situated in rows, generally mounted 1–3 m off the ground, depending on the racking and mounting system used. Other designs for solar panel deployment could mitigate, to some extent, the ongoing need for vegetation management (Fig. 2b,f), or allow grazing livestock to access vegetation under panels (Guerin, 2017). Rather than solar panels sitting close to the ground, if panels were situated at least 2 m above the ground at their lowest point, many grasses and shrubs would not grow tall enough to block the panels from sunlight. Further, this may allow additional vegetation types to be incorporated into solar facilities (e.g. shrubs and low woody vegetation) which could provide more habitat structural complexity, leading to increased biodiversity (Neilly et al., 2018; Nordberg and Schwarzkopf, 2019). Yet, to our knowledge, no solar facilities have experimented with the structural design of solar panels in this manner. Clearly, the additional costs of materials to place solar panels further above ground on solar farms would need to be offset by savings on vegetation management (mowing, spraying, etc.), dust control, and income from available environmental credits, and other revenue streams from producing food or fibre on the same sites. Conversely, on-ground solar arrays are now available that reduce the costs of deployment while minimizing ground disturbance. These low-profile placements may provide better habitat for some kinds of biodiversity, but may lead to increased panel fouling, or may interact with other processes in ways we do not yet understand. Irrespective of the designs deployed, such costs and benefits will need to be considered to optimise system performance. Again, independent of the solar technology deployed, system designs and solar panel arrangements could be improved by adding vegetation buffers, shrub and tree rows, and other patchy vegetation clusters to increase habitat and connectivity for wildlife, production of livestock and crops, and reduce run-off and erosion. What is certain is that leaving intact or restoring vegetation clusters and corridors can increase biodiversity and have positive impacts on species richness and diversity around agricultural landscapes (Burel, 1996; Nordberg et al., 2021).

5. Summary and future directions

Increasing generation of renewable energy has the potential to greatly reduce carbon emissions and diminish reliance on fossil fuels, but little is yet known about the effect of this expanding industry on the landscapes on which generation facilities are built, or the biodiversity associated with these sites and the ecosystem services they provide. We are similarly ignorant of how to minimize these impacts, or access the potential for better environmental and commercial returns, that could be realised through better design of solar facilities, in association with other land uses such as agriculture or conservation. It is clear, however, that the potential exists for increased net returns from co-locating power generation, agricultural production, and land restoration and conservation. To understand the size of this potential opportunity, studies quantifying the direct and indirect effects of solar farms on biodiversity and agricultural production, and vice versa, are needed. There is urgency in this need for greater understanding, especially given the current rapid growth of solar farm construction. As our knowledge of how to access these opportunities expands, the placement of new solar farms should be carefully considered to minimize negative effects on ecological communities, as should be the co-location of new facilities within existing disturbed agricultural landscapes. Designing mosaics of land uses that provide multiple economic benefits to multiple industries will reduce the negative effects of multiple land uses, and provide enhanced revenue for multiple industries, both through reduced maintenance costs and increased production. By designing future solar farms in partnerships with solar farm developers, agriculturalists, economists, and conservation ecologists, we can achieve more sustainable and regenerative outcomes for the environmental, agricultural, and power generation. Doing so will contribute to achieving many of the United Nations Sustainability and Development Goals (United Nations, 2015).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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