Review

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Uzair Jamil and Joshua M. Pearce *

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Review

Regenerative Agrivoltaics: Integrating Photovoltaics and Regenerative Agriculture for Sustainable Food and Energy Systems

Uzair Jamil [1] and Joshua M. Pearce [2,3,*]

[1] Department of Mechanical & Materials Engineering, Western University, London, ON, Canada
[2] Department of Electrical & Computer Engineering, Western University, London, ON N6A 3K7, Canada
[3] Ivey School of Business, Western University, London, ON N6A 3K7, Canada
* Correspondence: joshua.pearce@uwo.ca

Abstract: Regenerative agriculture has emerged as an alternative approach to food production, offering the potential to achieve reduced or even positive environmental and social outcomes compared to the soil degradation and greenhouse gas emissions of conventional agriculture. Simultaneously, a sophisticated dual-use system combining solar energy generation from photovoltaics with agricultural production called agrivoltaics is rapidly expanding. Combining these approaches into *regenerative agrivoltaics* offers a promising solution to the food challenge in a rapidly warming world. This review theoretically examines the compatibility and mutual benefits of combining agrivoltaics and regenerative agriculture, while also identifying the challenges, opportunities, and pathways for implementing this system. A foundation for advancing regenerative agrivoltaics is made by identifying areas for research, which include: 1) carbon sequestration, 2) soil health and fertility, 3) soil moisture, 4) soil microbial activity, 6) soil nutrients, 7) crop performance, 8) water-use efficiency, and 9) economics. By addressing the intersection of agriculture, renewable energy, and sustainability, regenerative agrivoltaics emphasizes the transformative potential of integrated systems in reshaping land use and resource management. This evaluation underscores the importance of policy and industry collaboration in facilitating adoption of regenerative agrivoltaics, advocating for tailored support mechanisms to enable widespread implementation of low-cost, zero-carbon, resilient food systems.

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1. Introduction

As the world population continues to grow so does the agricultural system that feeds humanity. To meet this need, farmers rely on fertilizers, pesticides, and land expansion, leading to a more than 60% rise in methane emissions from agriculture over the past four decades [1,2]. Although modern techniques have boosted productivity, they have also contributed to soil degradation, nutrient depletion, and pollution [3]. Practices including monoculture and excessive chemical application, have led to declining soil health, water contamination, and biodiversity loss, threatening ecological stability [4]. Agriculture remains a primary driver of greenhouse gas emissions (GHGs), responsible for over 11% of global anthropogenic emissions from direct sources [5]. If GHG emissions remain unchanged until 2100, crop yields will be reduced approximately by 45%, wheat yields by 50%, and rice yields by 30% [6]. These alarming projections highlight the urgent need to explore sustainable food production systems that can mitigate environmental impacts while ensuring long-term agricultural resilience.

1.1. Regenerative Agriculture: A Sustainable Approach to Food Production

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Regenerative agriculture (RA) has emerged as an alternative approach to food production, offering the potential to achieve reduced or even positive environmental and social outcomes [7]. Schreefel et al. defined RA as "an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting ecosystem services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production" [8]. It is increasingly recognized as a method to promote sustainability in food systems, with the added potential of contributing to climate change mitigation [9]. Project Drawdown [10], a nonprofit organization, with the aim to help the world stop climate change, emphasizes that RA improves soil health by replenishing carbon content, leading to greater productivity—an outcome that contrasts sharply with conventional farming practices [11]. Key agronomic challenges linked to RA include rebuilding soil health, capturing carbon to combat climate change, and reversing biodiversity loss [12]. With its numerous co-benefits, such as the production of nutritious food, RA is seen as a vital component in addressing the challenges posed by escalating climate instability [13].

1.2. Agrivoltaics: Integrating Energy and Agriculture

Clean energy technologies are taking a central role to achieving global sustainability goals [14]. Among these, solar photovoltaics (PV) has gained prominence as a cost-effective and rapidly expanding energy solution [15,16]. The extensive land requirements for traditional PV installations to meet the growing energy demands of an expanding global population often result in land use conflicts [17]. This is a particular problem if PV systems displace food production on agricultural land thereby running the risk of repeating the ethanol debacle and increasing food prices and global hunger [18].

Agrivoltaics, a dual-use system combining solar energy generation with agricultural production, offers a promising solution to this challenge [19]. Thie agrivoltaics approach provides numerous benefits, including lower greenhouse gas emissions (GHGs) [20], increased economic and environmental advantages [21], enhanced water-use efficiency [22–25], better land use efficiency [26] and perhaps most importantly increased crop yields of a wide variety of human food crops (basil [27], broccoli [28], celery [29], chiltepin peppers [26], lettuce [30,31], tomatoes [26], corn [32], strawberries [33,34], pasture grass [35,36], potatoes [37], Swiss chard [38–40], kale [38–40], and common bean [38–40], and grapes [40,41]).

Beyond agricultural productivity, agrivoltaics delivers multiple co-benefits, including protection of crops from environmental stressors such as wind [42], mitigation of soil erosion [43], and reversal of desertification [44]. Furthermore, the system improves solar module efficiency because of plant transpiration cooling the modules [45–47], alleviate agricultural displacement for energy requirements [48–50], localizes food production [51–53], improves health due to reduced pollution [54], acts as a hedge against inflation [55], provides energy for computing [56] and opportunities for integrating renewable fuel production, such as hydrogen [57–59], anhydrous ammonia [60] as well as the production of on-farm nitrogen fertilizers [61]. In addition improved nutrients (protein content) was also observed for spinach and basil under agrivoltaics configuration [27], which can further help to feed everyone [62].

The differences between regenerative agrivoltaics and conventional agriculture are summarized in Figure 1.

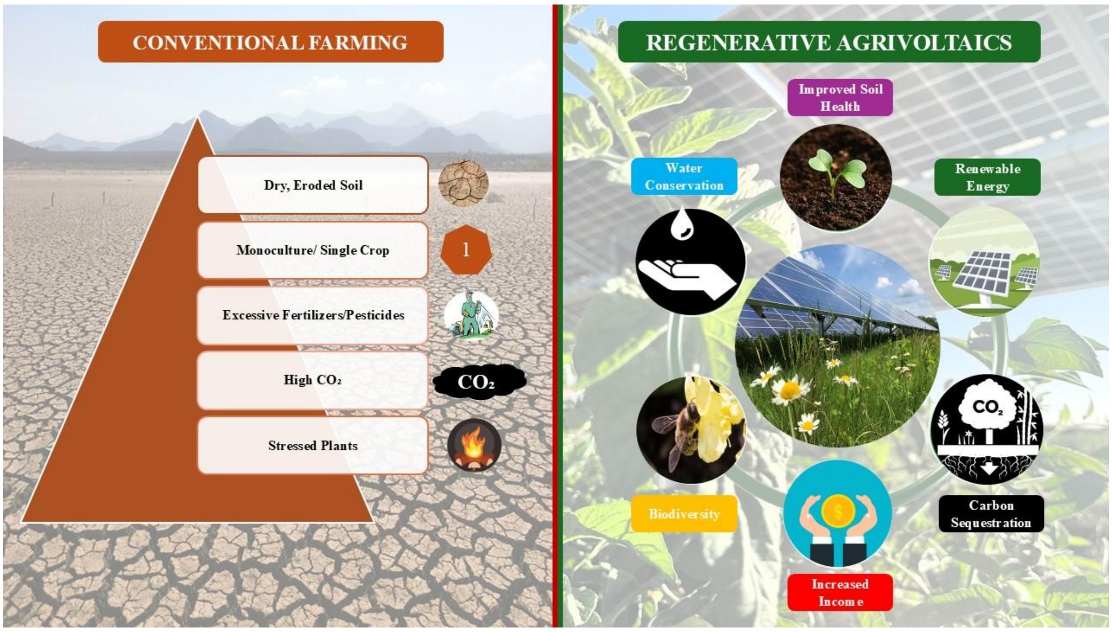

Figure 1. A comparison of conventional farming and regenerative agrivoltaics.

1.3. Economics and Market Growth of Agrivoltaics

From an economic perspective, agrivoltaics generates dual revenue streams through agricultural outputs and energy sales, enhancing farmers' financial stability [63]. For instance, spinach grown under agrivoltaic systems demonstrated financial gains of up to 35% alongside improved nutritional value [27]. Similarly, grazing sheep beneath PV arrays, not only creates a better environment for sheep but is highly profitable for solar shepherds that earn additional income from controlling vegetation on the solar farm [64]. These opportunities have been driving rapid growth in agrivoltaics, whose market is valued at over $3.64 billion in 2022 and is projected to grow at a compound annual growth rate (CAGR) of 38% between 2024 and 2030 [65]. As a strategy addressing both food security and energy sustainability, agrivoltaics holds significant potential to tackle critical global challenges, [66,67], highlighting the need for continued research and development in this area.

1.4. Combining Regenerative Farming and Agrivoltaics

Despite the growing interest in agrivoltaics and regenerative agriculture as independent approaches to sustainable land management, no prior research has explored the integration of these two systems. The potential synergy between agrivoltaics and regenerative agriculture remains largely unexplored, leaving a significant gap in understanding how these approaches could complement one another. This mini-review aims to theoretically examine the compatibility and mutual benefits of agrivoltaics and regenerative agriculture, while also identifying the challenges, opportunities, and pathways for implementing this innovative dual-use system. By bridging these fields, this article seeks to lay the groundwork for future research and practical applications in sustainable food and energy systems.

2. Fostering Resilience: Agrivoltaics Meets Regenerative Agriculture – Regenerative Agrivoltaic

The integration of agrivoltaics and regenerative agriculture offers a unique opportunity to enhance the environmental and economic benefits of each system.

By leveraging the complementary strengths of these approaches, society can address pressing challenges in sustainable agriculture and energy production. Agrivoltaics not only provides a means of clean energy generation, but also creates microclimatic conditions [68] that can bolster regenerative practices [69] such as cover cropping, composting, and organic annual cropping. Similarly, regenerative agriculture principles [70] scan enhance the sustainability of agrivoltaic systems by improving soil health, reducing chemical inputs, and increasing biodiversity. This convergence represents a holistic approach to land management that prioritizes resilience, productivity, and ecological health, creating a pathway to achieve multiple sustainability goals simultaneously. Specifically the U.N. Sustainable Development Goals [71] of : 2. Zero hunger, 3. Good health and well-being and 7. Affordable and clean energy, 14. Climate action, and 15. Life on land.

The following sections explore key areas of synergy between these two approaches, focusing on their potential to integrate cover cropping, composting, increasing crop diversity, and organic annual cropping within agrivoltaic systems. These innovations provide insights into how dual-use systems can be optimized to maximize co-benefits and establish a sustainable future for food and energy production.

3. Innovative Agrivoltaic Strategies for Regenerative Agriculture

Cover cropping, as highlighted in regenerative agriculture frameworks, has the potential to capture atmospheric carbon dioxide (CO_2) and sequester it in the form of soil organic matter [72]. This practice enhances soil biology, contributes essential nutrients to the soil [73], and mitigates soil erosion [74], thereby promoting healthier and more sustainable agroecosystems [75].

Agrivoltaics can bolster the efficacy of cover cropping, particularly under extreme weather conditions where the PV modules can act as shields for hail, for example. The shade provided by solar modules enhances the resilience of cover crops, preventing heat stress during high temperatures [76]. This might improve the ability of cover crops to build soil organic matter and sequester carbon. The combination of agrivoltaic systems and cover cropping can contribute to improved soil structure, and a reduction in erosion, furthering the goals of regenerative agriculture.

3.1. Cover Cropping

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3.2. Increasing Crop Diversity

Agrivoltaic systems can facilitate intercropping and polyculture practices by providing a modular layout that supports diverse planting configurations. This design enhances biodiversity [77,78] and builds resilience against climate variability [79,80]. Moreover, the microclimatic effects of agrivoltaics, such as moderated temperatures [29,45,81,82] and improved water efficiency [29,83,84], create favorable conditions for a variety of crops to thrive simultaneously. The integration of crop diversity into agrivoltaic systems aligns with regenerative goals of enhancing ecosystem services and increasing farm productivity.

3.3. Organic Annual Cropping

The integration of organic annual cropping into agrivoltaic systems offers a dual benefit of sustainable land use and environmental health. Organic farming practices, which rely on natural soil amendments and reduced chemical inputs [85,86], seems inherently compatible with agrivoltaics.

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The absence of synthetic pesticides and fertilizers minimizes the risk of PV module contamination or corrosion, reducing maintenance needs and associated costs. Additionally, the shade from modules can support crops prone to heat stress [87,88], aligning with the principles of low-impact, sustainable agriculture.

3.4. Composting

Enhancing soil organic matter is fundamental to restoring degraded soils [89]. Regenerative agriculture emphasizes the importance of incorporating composted biological materials, including crop residues, food scraps, and animal waste, to enrich soil health and fertility [90,91].

3.5. Animal Integration

Solar grazing presents an ideal opportunity for on-site soil improvement creating a closed-loop system for nutrient recycling. Animal waste from solar grazing can contribute significantly to enhance soil nutrients. The shade from solar modules can facilitate animal grazing [92], making the soil enrichment process more efficient in extreme climates as more animals would graze and benefit from shade [92]. Compost application within these systems not only improves soil fertility [93] but also reduces the need for external chemical fertilizers [94], contributing to energy-efficient and waste-reducing food production. This approach provides an avenue that enhances both soil health and environmental sustainability, while also lowering operational costs for farmers.

Agrivoltaics offer opportunities for livestock integration, combining vegetation management with enhanced soil fertility. Animals used on solar farms include sheep [64,83,95], rabbits [96,97] and now cows [92,98]. Grazing animals can maintain under-module vegetation, reducing the need for mechanical mowing [96], while their manure enriches soil organic content [99,100]. Furthermore, the shade provided by solar modules improves animal welfare by protecting livestock from heat stress [19,92,101], which can enhance productivity and health [95]. Integration of pasture based agrivotlaics systems have resulted in 69.3% less emission and 82.9% less energy requirements indicating highly sustainable food-energy system [97]. This synergy exemplifies a holistic approach to regenerative agriculture, optimizing land use for food, energy, and livestock production.

3.6. Managed Grazing

Rotational grazing under solar modules presents a viable strategy for pasture regeneration and carbon storage [102]. By controlling grazing patterns, farmers can ensure even vegetation coverage, and reducing overgrazing risks [96]. The shade from modules creates microclimate that promote diverse forage growth [35,103], supporting livestock nutrition and ecosystem health. Managed grazing within agrivoltaic systems offers a scalable solution contributing to dual-use land management.

3.7. Reduced/No-Till Farming Practices

Undisturbed soils foster an increase in both the abundance and diversity of soil microbial communities, contributing to enhanced soil structure and overall microbiome health [104]. Farmers who implement reduced or no-till practices can experience numerous advantages that not only improve soil health but also provide long-term economic benefits [105]. These practices enhance water infiltration and retention, improve nutrient retention and availability for crops, reduce soil crusting, and lead to a gradual accumulation of soil organic matter, collectively promoting more sustainable and resilient agricultural systems [105,106].

Pairing no-till farming with agrivoltaic systems presents significant potential to enhance soil health and water retention. The partial shade provided by solar modules reduces soil surface temperatures [33,68,107], minimizing water evaporation and fostering a microclimate conducive to moisture retention [84,108]. This synergy supports no-till practices by reducing the likelihood of soil compaction, especially as the shade mitigates the direct impact of heavy rain. Furthermore, the

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reduced soil disturbance inherent in no-till systems aligns with the fixed nature of agrivoltaic infrastructure, promoting long-term soil stability and resilience. From the PV side, reduced tilling would also reduce the risk of module soiling, which can cause a decrease in energy conversion efficiency [109].

3.8. Silvopasture/Agroforestry

Integrating silvopasture or agroforestry with agrivoltaics presents a promising avenue for long-term sustainability. Integrating agrivoltaics with apple trees have shown reduced water needs [108]. Designs that incorporate trees, solar modules, and grazing animals create a multi-layered system capable of delivering carbon sequestration [110,111], soil fertility [111], and diversified farm incomes [27,80,112–114]. The shade from trees and modules moderates temperature extremes, improving animal welfare [19,92,101] and forage quality [103]. Additionally, the long-term carbon storage provided by trees [115] complements the renewable energy benefits of agrivoltaics, positioning these systems as a cornerstone of sustainable land-use practices.

4. Unlocking the Potential of Regenerative Agrivoltaics: Synergies, Challenges, and Theoretical Contributions

4.1. Synergies and Opportunities

Agrivoltaics serves as a powerful catalyst for advancing regenerative agricultural practices by addressing land-use competition while enhancing economic viability. By integrating solar energy systems with farming, agrivoltaics enables dual land use, reducing the need to dedicate vast areas solely for energy production. This synergy creates opportunities to scale regenerative practices, fostering climate resilience through improved soil health, water retention, and carbon sequestration. Additionally, agrivoltaics enhances ecosystem services by supporting biodiversity, providing shade, and creating microclimates conducive to crop growth. With the potential to diversify farm outputs and generate renewable energy, agrivoltaics not only bolsters farm income but also strengthens the sustainability and resilience of agricultural landscapes.

4.2. Challenges and Barriers

Despite its promise, agrivoltaics faces significant challenges in aligning system design and operations with regenerative agricultural goals. The complexities of optimizing dual-use systems to balance energy production, crop growth, and ecological benefits require innovative engineering and site-specific solutions. For instance, specialized racking solutions may be required for integrating solar PV modules with agriculture on which limited work/research has so far been performed [116–118]. Furthermore, the absence of tailored financial models and incentives for dual-use regenerative systems hinders widespread adoption, as farmers and developers often lack the economic support necessary to transition.

The absence of well-defined government policies integrating sustainable agriculture and renewable energy development presents another barrier to the widespread adoption of regenerative agrivoltaics. Establishing clear policy frameworks could provide crucial guidance and incentives, encouraging stakeholders to adopt practices that enhance both food production and clean energy generation. These policies, however, should be informed by empirical research exploring the intersection of agrivoltaics and regenerative agriculture.

Future experimental studies could focus on addressing the knowledge gaps to generate empirical evidence that demonstrates the long-term viability and benefits of agrivoltaics. Assessing soil health and fertility under agrivoltaic systems, evaluating carbon sequestration potential, and analyzing the benefits of incorporating animal and crop waste as soil amendments are important parameters to examine during such experiments. Additionally, trials could investigate the impacts of shading from solar modules on soil moisture retention, microbial activity, and nutrient cycling.

Evaluating crop performance under varying solar modules configurations and transparency levels, as well as measuring water-use efficiency and microclimatic modifications, would further contribute to optimizing system design. These research efforts are essential for generating the empirical evidence needed to shape effective policies and scale regenerative agrivoltaics as a viable solution for sustainable food and energy production. Addressing these challenges is crucial for unlocking its full potential as a sustainable farming and energy solution.

5. Conclusions

This review lays a critical foundation for advancing regenerative agrivoltaics by identifying key areas ripe for innovation and development, which include: 1) carbon sequestration, 2) soil health and fertility, 3) soil moisture, 4) soil microbial activity, 6) soil nutrient, 7) crop performance, 8) water-use efficiency, and 9) regenerative-agrivotlaics economics. By addressing the intersection of agriculture, renewable energy, and sustainability, regenerative agrivoltaics emphasizes the transformative potential of integrated systems in reshaping land use and resource management. Furthermore, the evaluation underscores the importance of policy and industry collaboration in facilitating the adoption of regenerative agrivoltaics, advocating for tailored support mechanisms to enable widespread implementation. By bridging knowledge gaps (soil health impacts, optimal module configuration, water-use and microclimate effects, biodiversity implications, livestock and composting integration effects, economic feasibility, policy gaps, long term empirical field studies, farmer engagement research) and highlighting opportunities (biodiversity benefits, enhancement of soil regeneration, improving water efficiency, increasing farm revenue streams) for synergies, this research provides a framework to guide future studies and inform practical applications in dual-use agricultural systems.

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