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Vegetation management utilizing sheep grazing within utility-scale solar: Agro-ecological insights and existing knowledge gaps in the United States

W.C. Stewart^a, J.D. Scasta^b, C. Maierle^c, S. Ates^d, J.M. Burke^e, B.J. Campbell^{f,*}

^a Department of Animal Science, University of Wyoming, Laramie, WY, USA

^b Department of Ecosystem Science and Management, University of Wyoming, Laramie, WY, USA

^c The American Lamb Board, Denver, CO, USA

^d Department of Animal and Rangeland Sciences, Oregon State University, Corvallis, OR, USA

^e Dale Bumpers Small Farms Research Center, Agricultural Research Service, United States Department of Agriculture, Booneville, AR, USA

^f Department of Animal Sciences, The Ohio State University, Wooster, OH, USA

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ABSTRACT

Common themes exist in the development of photovoltaic (PV) systems, globally. Capturing sunlight for energy production requires a significant land-use footprint, thus resulting in limitations that prohibit development of solar sites. Diverse regions across the U.S. are being utilized for PV development with varying population density, climate, and forage production potential. Energy usage is expected to grow with increased demand from industrial and residential segments. Internationally, the U.S. ranks second in energy usage and is the primary contributor to the growing energy demand. As utility-scale solar installations continue to expand across the U.S., and specifically pastures and rangelands, the need for sustainable vegetation management has become a critical operational consideration. Grazing with sheep presents a viable solution, offering both economic and ecological benefits by controlling vegetation growth without compromising (PV) panel efficiency. This review synthesizes current research on the integration of sheep grazing within solar sites, often referred to as "solar grazing," with a focus on the agro-ecological interactions, operational challenges, and potential for industry growth. This review also examines the critical factors influencing vegetation management, including regional climate variability, forage production potential, and species-specific grazing behaviors. Additionally, the role of solar grazing in fire mitigation, biodiversity enhancement, and soil health improvement is explored. Despite the promise of this dual-use strategy, several knowledge gaps persist, particularly regarding the long-term ecological impacts on native plant communities, optimal sheep stocking densities, and the balance between forage production and sheep nutrition within these solar sites. Current trends in solar development are contrasted with the declining sheep population in the U.S., raising concerns about whether the American sheep industry can meet the growing demand for solar grazing. Moreover, the integration of solar grazing introduces new challenges in animal health and welfare, particularly in regions with increased parasite concentrations or limited access to water and supplemental feed. This review highlights the need for further research on adaptive management practices, as well as the development of infrastructure and industry support to ensure the sustainability of solar grazing in diverse regions of the U.S.

1. Introduction

The global shift toward renewable energy production has led to the rapid expansion of photovoltaic (PV) systems (IEA, 2024). Utility-scale solar energy in the U.S. has rapidly expanded, with over 200,000 MW of installed capacity and projections of 30,000–40,000 MW of additional installations annually through 2029, which will require significant land

resources including pastures and rangelands and creating opportunities for agrivoltaic systems like solar grazing (SEIA, 2024). Sheep grazing for vegetation control within PV systems, known as "solar grazing," builds upon the long-established practice of using livestock for targeted grazing to achieve specific vegetation management goals (Launchbaugh and Walker, 2006) and has rapidly expanded in the U.S.; particularly in the Southwest, Midwest, and East coast regions of the continental U.S.

* Corresponding author.

E-mail address: campbell.1279@osu.edu (B.J. Campbell).

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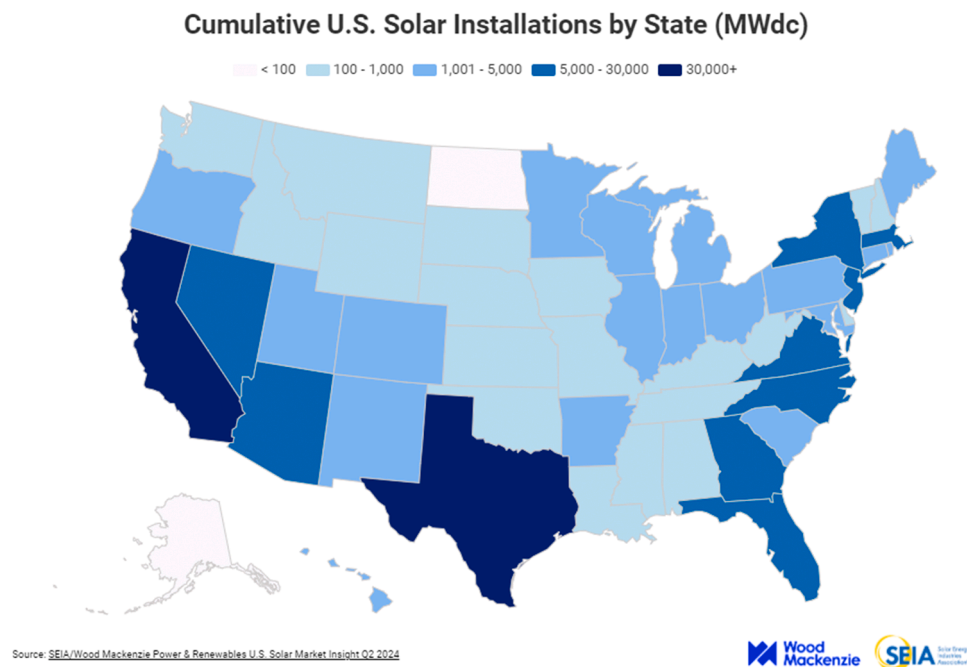


Fig. 1. Solar Energy Industries Association (SEIA) cumulative U.S. solar installation estimates by state as of June 2024 (SEIA, 2024).

(Fig. 1). However, significant knowledge gaps exist in research within utility-scale (>1.0 MW) agrivoltaic systems integrating livestock grazing, particularly in regions where solar potential and grazing activities overlap. Therefore, comprehensive studies are needed to optimize these systems for sustainable energy and land management (Mamun et al., 2022). For example, sheep are well-suited for this role as their size and grazing habits manage vegetation by preventing panel shading and reducing fine fuels for wildfire risk, without damaging solar infrastructure (Andrew et al., 2021). Moreover, the use of sheep for vegetation management offers a sustainable alternative to mechanical mowing, which can be costly and less environmentally friendly (McCall et al., 2023). Furthermore, a study in Arizona, Colorado, Oregon, and Utah revealed that use of livestock grazing for vegetation management is a more uniformly accepted strategy when compared with other vegetation management options such as mechanical removal and prescribed fire (Brunson and Shindler, 2004). While the potential benefits of solar grazing are well-documented, the practice remains under-researched, particularly in the context of diverse agro-ecological zones in the U.S. Solar grazing presents unique challenges that vary by region, including differences in forage availability, climate variability, and land-use history. In addition, the decline in U.S. sheep populations presents an operational challenge for scaling up solar grazing to meet the immediate demands of the rapidly expanding solar energy sector. This review aims to provide a comprehensive current challenges and opportunities listing of solar grazing in the U.S., highlighting the diverse agro-ecological interactions that influence vegetation management success, the operational challenges and opportunities faced by solar graziers, and the existing knowledge gaps that limit the optimization of this multi-use land management strategy. This review will also explore the potential of solar grazing to contribute to broader environmental and agricultural goals, such as carbon sequestration, biodiversity enhancement, and sustainable livestock production. By synthesizing the available literature and identifying critical areas for future research, this review intends to provide insights that will support the continued development and scalability of solar grazing as a sustainable solution for utility-scale solar projects while optimizing for a vibrant U.S. sheep industry.

2. Overview of the solar industry landscape

As utility-scale solar energy installations expand across diverse regions of the U.S., the need for effective and sustainable vegetation management has become increasingly critical. Integrating sheep grazing within solar arrays, commonly referred to as "solar grazing," offers an innovative solution with significant agro-ecological and economic potential. This dual-use approach leverages sheep as natural vegetation managers, reducing fire risk, and ensuring that photovoltaic (PV) systems remain efficient by preventing panel shading (Andrew et al., 2021). Despite its promise, several challenges remain underexplored, including the long-term impacts on native plant communities, optimal sheep stocking densities, and managing sheep health under varying climatic conditions (Kampherbeek et al., 2023; Andrew et al., 2024). Furthermore, the declining U.S. sheep population presents a challenge to the immediate scalability of solar grazing to meet the demands of the growing solar industry (USDA NASS, 2024). This review will examine these issues in greater depth, highlighting existing knowledge gaps and discussing opportunities for solar grazing to enhance biodiversity, improve soil health, and contribute to sustainable livestock production. This review will also explore adaptive management strategies and infrastructure development necessary to support the widespread adoption of solar grazing across diverse agro-ecological zones in the U.S.

2.1. Agrivoltaic development in the United States

Over the last decade, the U.S. has seen an increase in photovoltaic (PV) solar energy production, with much of this focus revolving around utility-scale solar. Although the definition of utility-scale solar will vary based upon institution, the National Renewable Energy Laboratory (NREL), the nation's leader in renewable energy production, defines utility-scale solar as a ground mounted solar system, which include fixed-tilt and one-axis tracker systems, that has the capacity to generate 5 – 100 Megawatts (MW; Feldman et al., 2021). To put this into perspective as it relates to land mass requirements, Wyatt and Kristian (2021) conservatively estimated that for each MW of electricity produced, a solar development footprint of 4.05 ha will be required. Granted, land mass needs will vary based upon geographic location (e.g., light intensity and weather patterns) and quality of hardware and

U.S. Solar PV Deployment Forecast

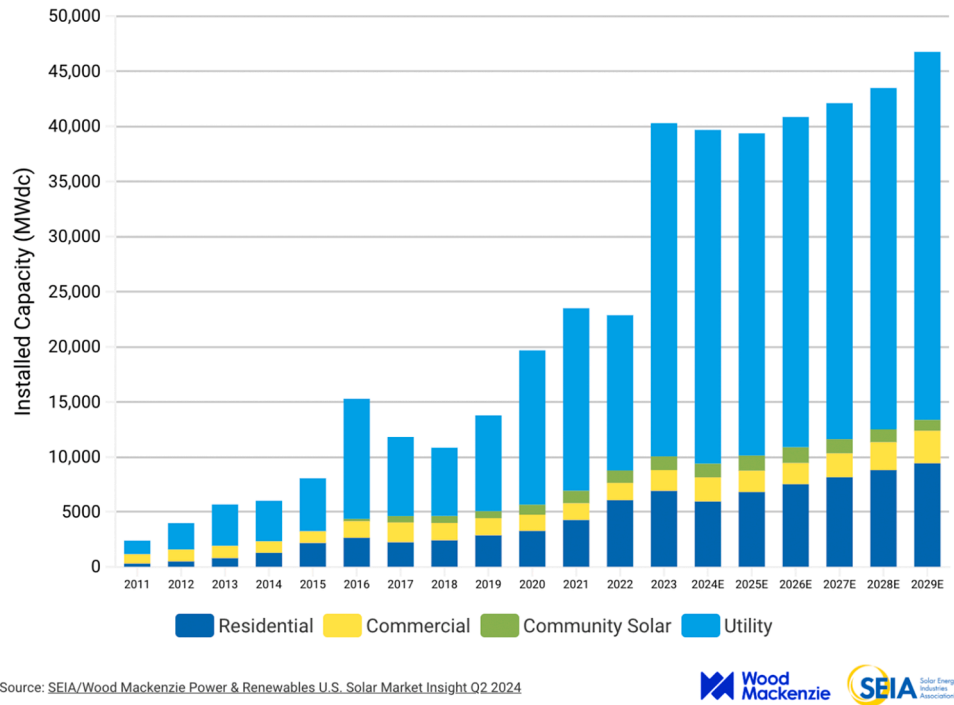


Fig. 2. Solar Energy Industries Association (SEIA) solar photovoltaic current deployment (2011 – 2024) and future deployment forecast (2025 – 2029) which includes commercial, community solar, residential, and utility solar operations (SEIA, 2024).

equipment used within a solar site. According to the Solar Energy Industries Association Q2 report (SEIA, 2024), when accounting for all types of solar installations (*i.e.*, commercial, community, residential, and utility), the U.S. currently has over 200,000 MW of solar energy generating capacity today (Fig. 2). Furthermore, SEIA (2024) also predicts an additional 30,000–40,000 MW of utility scale solar installations to be established each year through 2029 (Fig. 2). Over this five-year span alone, a total of 607,500 to 810,000 ha of additional land will be required for utility-scale solar installations.

As for any type of energy generation system, to remain efficient, power must be generated near a connecting energy transmission grid. As highlighted in Fig. 1, solar installations typically follow energy demands and needs based upon population or industry consumption. Population is not the only factor when considering the ideal location for solar installations. As outlined in the Department of Energy (DOE) Solar Energy Technologies Office (SETO) funding announcement for the Foundational Agrivoltaic Research for Megawatt Scale (FARMS), solar energy deployment is most favorable in areas that are large in scale or size, sunny, and flat, such as traditional agronomic row crop landscapes (DOE FARMS, 2022). This requirement alone highlights the challenges and negative connotations associated with large-scale solar site acceptability in rural communities. However, rather than focusing on the loss of farmland, agrivoltaics or the process of farming within solar sites, aims to incorporate multi-use land management strategies to combine PV energy and agricultural (*i.e.*, agronomic crop and livestock) production systems on the same unit of land. A variety of agrivoltaic research has been conducted, exploring the integration of solar energy production with different agricultural practices. These works include pairing solar panels with specialty vegetable crops (Chae et al., 2022; Mohammadi et al., 2023; Scarano et al., 2024), pollinator and native seed plantings (Graham et al., 2021; Semeraro et al., 2022), livestock grazing (Andrew et al., 2021; Kochendoerfer et al., 2021; Sharpe et al., 2021; Kampherbeek et al., 2023; Andrew et al., 2024), as well as grain and forage production (Sturchio et al., 2022; Grubbs et al., 2024) within PV systems. Among these systems, managing vegetation with sheep offers both

challenges and opportunities as it presents a sustainable approach to optimize PV efficiency while effectively utilizing forage resources for sheep production.

2.2. Vegetation management

Vegetation management of grass, forbs, and woody plant species within solar systems is critically important for the optimization of PV energy production and ensuring the sustainability of agrivoltaic systems. Effective vegetation management not only prevents shading and wildfire risk, but also ensures the ecological health of the site. Shading from PV panels can significantly affect herbage yield and quality. Weselek et al. (2021) reported that fully shaded areas experience reduced yields, with volunteer grasses often dominating. Furthermore, in partially shaded areas, grass-clover mixed pastures experienced yield reductions of 5–8%. Additionally, while shading may enhance nitrogen (N) concentration in forages, it reduces water-soluble carbohydrates, thus potentially decreasing forage quality (Ciavarella et al., 2000; Dodd et al., 2005; Andrew et al., 2021; Portner et al., 2023). As a baseline for guiding sustainable grazing practices, vegetation management strategies should align with agroecological zoning guidelines. These guidelines, developed by organizations like the Food and Agriculture Organization (FAO), provide a framework to ensure that land use and grazing practices are compatible with the ecological characteristics of the region, such as soil type, climate, and vegetation patterns, which can vary significantly across solar development sites (FAO, 1996). By integrating agroecological zoning principles, solar grazing can be adapted to harmonize vegetation management goals and support sustainable land use specific to the agroecological site.

Because of the diverse climates and landscapes across solar development regions, vegetation management demands vary considerably. For example, in arid, wildfire-prone environments, residual fine-fuel loads within or outside a solar system can create significant risk and concern to site integrity and infrastructure (McCall et al. 2023). Grazing sheep and goats to reduce fire fuel loads has proven to be an effective

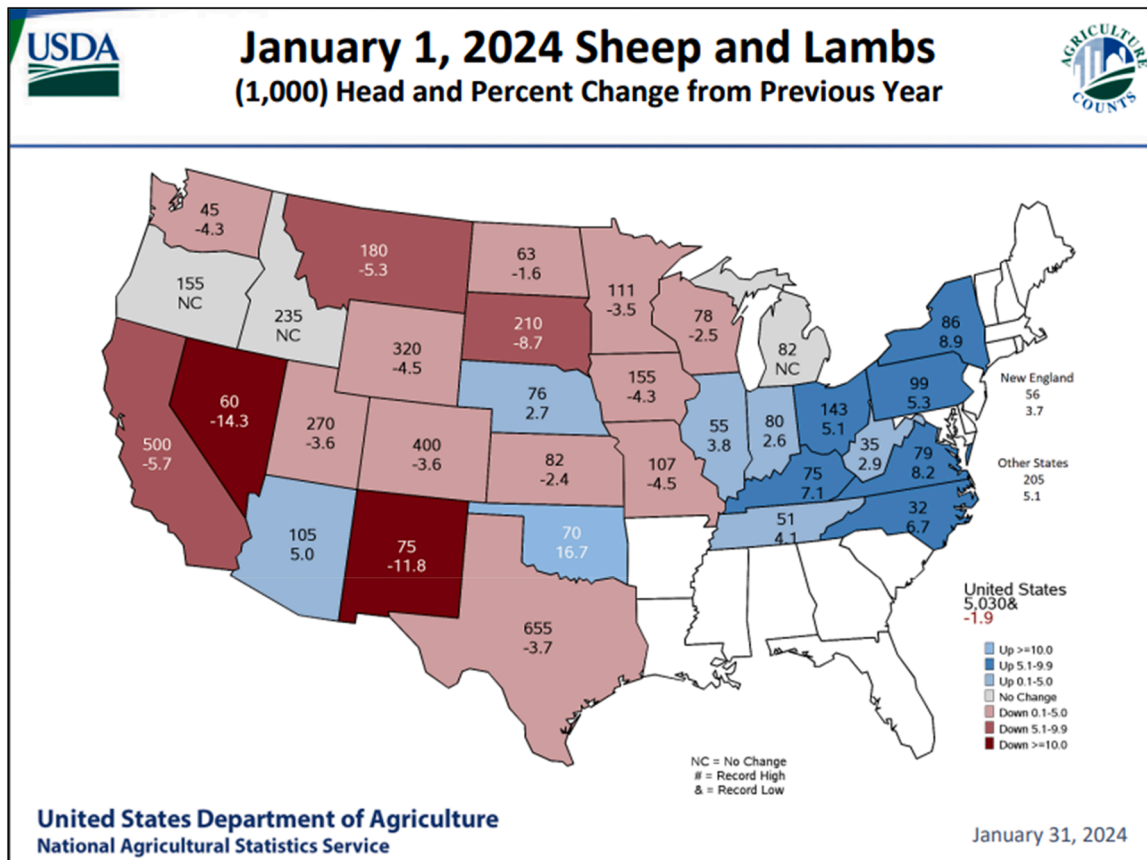


Fig. 3. United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS) U.S. map illustrating sheep and lambs headage (1000) and percent change from the previous year as of January 1, 2024 (figure provided by USDA NASS, 2024).

strategy in these regions and in Europe (Taylor, 1994; Strand et al., 2014; Log et al., 2022; Nuss-Girona, 2022). Applying this strategy within solar systems helps protect solar assets and reduces the risk to neighboring properties. Fire prevention remains a significant concern across all solar regions, especially those in semi-arid or drought-stricken areas, as dry vegetation comes in contact with exposed wires or lightning, resulting in fuel ignition leading to wildfires (Schwab et al., 2020). Therefore, managing forage height is critical for maintaining energy production efficiency in agrivoltaic systems.

Additionally, overgrown vegetation will result in panel shading, thus reducing panel efficiency particularly in agroecosystems with high rainfall, where rapid plant growth and solar panel encroachment is a common concern. In such areas, forage utilization rates of 80 % or greater may be necessary to prevent shading. It should be noted here that forage utilization in high rainfall systems may also encompass animal trampling/waste to reduce plant height rather than dry matter remaining post grazing. In contrast, semi-arid high plains regions, where prostrate forage is typical, require a different approach. In these regions, vegetation management is mainly focused on limiting fine fuel loads to prevent wildfires, which may necessitate removing a higher percentage of forage biomass. Ultimately, understanding the growth of specific forage species within each region will play a critical role in providing guidance on utilization recommendations for the implementation of successful grazing, forage, and vegetation management strategies with implications for the sustainability of native plant communities. These regional differences highlight the need for additional research to determine optimal residual forage heights and grazing utilization strategies that balance vegetation control with long-term ecological sustainability.

2.3. Utilizing sheep to meet agrivoltaic vegetation management demands

Challenges with utilizing sheep as a primary form of vegetation management in solar farms is inevitable. Unlike cattle, which are larger and could potentially damage the infrastructure, or goats, which tend to climb and chew on equipment, sheep are smaller and less likely to cause harm. Their grazing habits are also ideal for managing vegetation under the panels without disrupting the PV system. This makes sheep a favorable choice for maintaining the site, while other classes of animals may not be as suitable unless site development and infrastructure has accounted for challenges and management needs associated with the selected livestock species. Conversely, a primary concern exists around the opposing trends between the U.S. sheep industry inventory and solar development. Sheep production in the total sheep breeding population has decreased since 1884 when inventory peaked at 51 million head (USDA ERS, 2022). Today, the breeding population is recorded at 5.03 million total head (USDA, NASS, 2024). In addition to live animal inventory decline, consumer demand for lamb has driven imports to account for more than half of lamb consumed in the US (USDA ERS, 2022). In contrast to U.S. sheep historic inventories, utility-scale solar developments have grown exponentially in the last decade (Fig. 2). Solar energy is relying heavily on the American sheep industry to support the agrivoltaics commitments proposed by solar developers and state governing bodies alike. To fulfill these commitments, the US sheep industry will require significant expansion.

As outlined by Warren (2023), from an operations standpoint, grazing is a sustainable solution as in most cases it is the most cost-effective option when compared with mowing at any scale of a solar site. Because of their adaptability, behavior, and current economic value, sheep easily fit a utility-scale solar farm vegetation management plan. McCall et al. (2023) found that the median cost for sheep grazing in

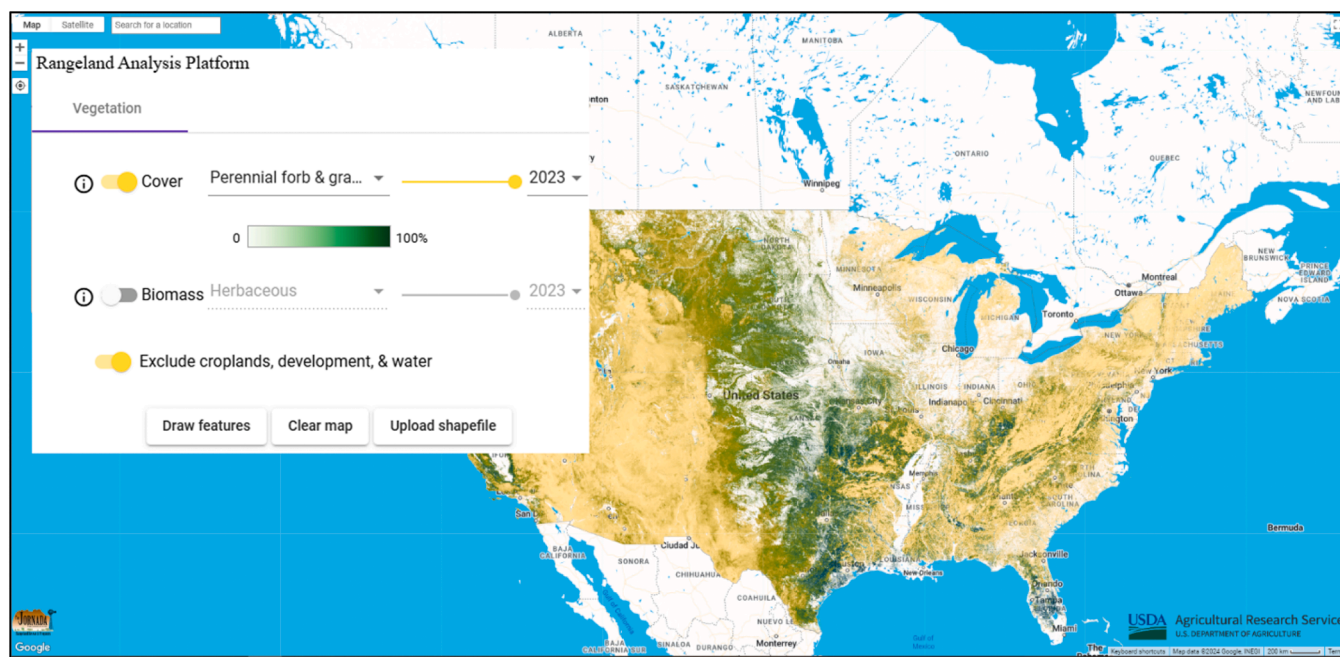


Fig. 4. Rangeland and pastures of the United States have variable forage production potential as demonstrated in this map from the Rangeland Analysis Platform (<https://rangelands.app/>) and subsequently sheep grazing recommendations within solar systems must be tailored to the environmental context in which they exist.

utility-scale solar sites was \$279/hectare/year, which was slightly lower than mowing costs (\$299/hectare/year) and significantly less than herbicide application in gravel sites (\$724/hectare/year). The total combined maintenance costs for sheep grazing averaged \$758/hectare/year, making it a competitive option compared to other vegetation management practices, despite potentially greater input costs for fencing, water hauling, and grazing schedule management. According to preliminary results from the first U.S. Solar Grazing Census conducted in 2024 by the American Solar Grazing Association (ASGA, 2024) and sponsored in part by NREL, the average number of sheep being grazed by custom and contract shepherds operating within solar farms providing vegetation management services is approximately 1300 head per grazier (ASGA, 2024). However, it is worth noting that this number reflects the total number of sheep managed per solar grazier and does not represent the number of sheep grazed per site. The average number of animals grazed per site, or unit of area are forthcoming through additional survey work provided by ASGA. Furthermore, ASGA (2024) also reports approximately 40,469 ha of land are currently being grazed in the U.S. by contract graziers active within the organization with graziers managing close to 600 ha each. However, these data should also be interpreted with caution as this metric fails to account for those that did not complete the survey or are not currently members of ASGA.

To accomplish this feat, the current U.S. sheep and lamb inventory will need to increase substantially. As outlined in Fig. 1, California and Texas are the nation's leaders in solar energy production, with greater than 60,000 MG of electricity being produced. These two states also represent the top two sheep producing states in the U.S. totaling nearly 785,000 head of total breeding sheep and lambs, or 15.6 % of U.S. sheep breeding inventory (USDA, NASS, 2024).

The rapid expansion of solar installations, projected to grow by 30,000–40,000 MW annually through 2029, will require an additional 607,500 to 810,000 ha of land (SEIA, 2024). This growth, particularly in the Eastern and Midwestern U.S., underscores the need to increase sheep inventories for vegetation management, as solar developers favor grazing for its cost efficiency (McCall et al., 2023), environmental benefits, and public perception (Warren, 2023). As highlighted in Fig. 3, states like Ohio (+5 %), Pennsylvania (+5 %), Kentucky (+7 %), and New York (+9 %) have shown total sheep and lamb inventories increase

from 2023 to 2024 (USDA NASS, 2024), but sheep numbers in many other critical solar development areas such as Michigan (+0 %), Wisconsin (−2.5 %), and Minnesota (−3.5 %) may still fall short of meeting growing demand (USDA NASS, 2024). In the Western region of the U.S., very few states have seen an increase in sheep and lamb inventories while leading solar deployment and sheep producing state states like California (−6 %) and Texas (−4 %) have shown drastic decreases in sheep and lamb numbers (USDA NASS, 2024). This variation across regions highlights the need for more targeted efforts to boost sheep availability in areas where solar grazing is expanding (Mamun et al., 2022). Regions, particularly in the Eastern and Midwestern U.S., will need to increase flock sizes to meet current and future solar grazing demands. Grazing contractors must decide between internal expansion via ewe-lamb systems, requiring capital investment, or contracting with larger operators for maintenance ewes, breeding replacements, or feeder lambs. Outsourcing necessitates strict biosecurity to prevent disease transmission and manage anthelmintic-gastrointestinal nematode resistance.

3. Agriculture and ecology considerations

3.1. Solar grazing: Opportunities and considerations

Solar development has proliferated in the Eastern, Midwest, South, and Southwestern regions of the U.S., while growth has lagged in semi-arid regions of the Great Plains and Intermountain West (Fig. 1). Solar grazing presents significant opportunities for sheep producers in all these regions, but the diverse agroecological zones highlight the need for region-specific management strategies. In the Eastern and Midwestern U.S., where annual precipitation ranges from 75 to 150 cm, excessive forage growth can pose challenges for managing vegetation within solar farms and under solar arrays during the growing seasons. Conversely, in semi-arid regions of the high plains and Intermountain West, where precipitation can be as low as 25–50 cm, grazing systems face different challenges, particularly in managing low productivity rangelands under extensive production systems. These regions also differ in soil type and climate, underscoring the need for best management practices that are tailored to specific agroecological conditions, all of which influence

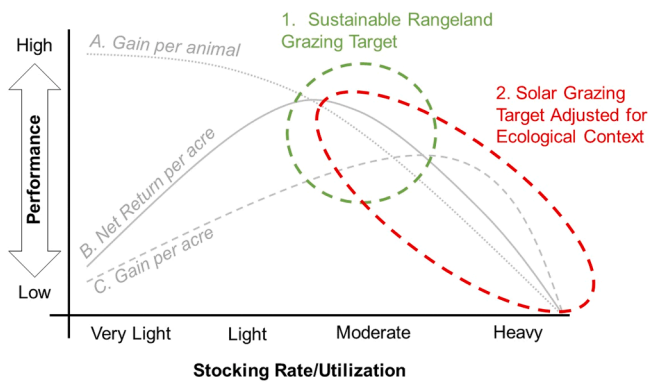


Fig. 5. Animal and land performance metrics relative to stocking rates and utilization with considerations for sustainable rangeland grazing and solar grazing for vegetation management (adapted from Redfearn and Bidwell, 2003). For solar grazing, there may need to be greater levels of utilization to achieve vegetation management objectives. Such management will require monitoring and information feedback loops to adapt relative to ecosystem management, economic, and animal performance indicators.

herbaceous forage production, appropriate stocking rates, and utilization goals (Fig. 4).

Collaboration with regional agroecological and sheep production professionals is essential to ensure that solar grazing practices benefit both the land and livestock while maintaining sustainability of the grazing system. The map of solar development trends (Fig. 1) highlights these regional differences and reinforces the importance of aligning grazing, forage, and vegetation management practices in respect to the distinct agroecological characteristics of each zone.

3.2. Vegetation management goals vs. good grazing management

An often-overlooked aspect of vegetation management is meeting livestock's nutritional needs at different production stages. Aligning animals' physiological demands with the most nutritious plant stages at light to moderate stocking rates can enhance growth or maintain body condition of livestock (Fig. 5). Achieving a balance between vegetation control and optimal animal performance is not always feasible, as certain vegetation management goals may require greater levels of biomass utilization (Launchbaugh and Walker, 2006; Fig. 5). Generally, as utilization increases, individual animal gains decline, while gains per hectare and net return per hectare rise (Redfearn and Bidwell, 2003). However, once utilization surpasses moderate levels, all three metrics—individual gains, gains per hectare, and net return—tend to decrease (Animut et al., 2005; Bement, 1969; Botha et al., 1993; Dermer et al., 2008; Hart et al., 1988; Holechek et al., 1995; Redfearn and Bidwell, 2003; Sharrow et al., 1981; Wang et al., 2011; Fig. 5). This matrix alone brings light to the complexity of this type of grazing system. Based upon operational goals, grazing or vegetation management contracts, as well as quality and yield of biomass to be maintained, livestock management will vary greatly.

In addition, the continuous use of intense grazing has the potential to degrade pastures and rangelands alike in both forage production and condition with economic consequences as well (Holechek et al. 1995). The degradation in environmental conditions would be an outcome of the selection for and against certain types of plants, specifically selection for less desirable plants and selection against more desirable plants (Launchbaugh, 1969; Willms et al. 1985; Holechek et al. 1995). As evidence of potential differences between sustainable pasture and rangeland grazing versus targeted grazing for vegetation management, Bailey et al. (2019) states “Targeted grazing differs from traditional grazing management in that the goal of targeted grazing is to apply defoliation or trampling to achieve specific vegetation management objectives, whereas the goal of traditional livestock grazing management is generally the production

of livestock commodities.” It is therefore necessary to develop ecological goals for grazing within solar installations for vegetation management that optimize livestock production, soil health, vegetation management, water quality, and wildlife cohabitation in a sustainable manner.

Targeted grazing for different applications of vegetation management have been proposed including for invasive weeds, fine-fuel management and fire reduction, and now solar grazing. Utilization rates for fire mitigation, specifically in semi-arid regions, will impact plant communities differently than controlling vegetation to reduce shading in temperate, high-rainfall areas. Claims of maintaining native communities under intensive and continuous sheep grazing bouts may be unrealistic as vegetation changes under such pressure.

A meta-analysis by Stahlheber and D'Antonio (2013) for California's Mediterranean grasslands highlights the complexity of grazing's effects on plant cover and richness. Grazing increases exotic forb cover, like *Erodium cicutarium*, without enhancing their richness. Native forb richness increases variably depending on grazing regime and precipitation. Native grasses generally show increased cover with grazing, though results were highly variable. Lwiwski et al. (2015) evaluated the effects of stocking rate in a northern mixed grass prairie in Canada and found that stocking rate differentially affected plant species richness with increases in uplands and decreases in lowlands as stocking rate increased. Similarly, Gillen et al. (2000) conducted a study in the southern mixed grass prairie and found that stocking rate was not as strong of a driver for vegetation change. Yet many of these studies are also predominantly cattle grazing, and thus more sheep grazing studies will be needed to guide graziers' decision making across diverse agro-ecological sites and particularly guided by feedback and adjustments if undesirable vegetation changes occur. Nonetheless, the effectiveness of grazing is context-dependent, influenced by soil type, precipitation, and grazing regime. The potential for increases of exotic or non-target species and reductions in species richness are of concern for ecological function. Therefore, in addition to monitoring, adaptive grazing strategies will be necessary to manage these variations and balance benefits with potential increases in exotic forbs, particularly in low-precipitation areas. This likely will need to be considerations for not only the intensity and utilization as discussed already, but also timing relative to plant phenology and associated plant responses.

To achieve vegetation management objectives for solar grazing, best management practices should align with established principles of pasture and rangeland ecology and management, as well as research on crop-livestock integration to enhance carbon sequestration and agroecosystem functioning. Strategies should promote native (particularly if in a native rangeland), perennial, diverse, shade-tolerant, and drought-resistant forage species to improve soil health and carbon sequestration. Adaptive practices considering precipitation variability and soil type can optimize productivity and resilience. A Prescribed Grazing Plan (PGP) balances vegetation management and ecosystem health by guiding decisions on stocking rates, grazing periods, animal classes, vegetation standards, and soil conditions (Briske et al., 2011; Bailey et al., 2019; McCall et al., 2023). When correctly implemented and regularly revisited, this plan enables graziers to adjust practices for healthier plant communities, reduced erosion, and more predictable outcomes. However, more robust datasets on vegetation and animal performance from diverse solar grazing sites are needed to adapt these tools beyond traditional grazing paradigms (Sanderson et al., 2009; USDA, 2020), as solar grazing requires dynamic, tailored decision-making tools for both plant and animal benefits. Given the rapid advent of solar grazing practices, assessing the capability of existing tools for solar grazing applications is an excellent collaborative opportunity for solar graziers, government and state researchers, and Extension educators. Collaboration among solar graziers and developers alike to implement these practices can enhance renewable energy production and environmental sustainability, leading to resilient and productive systems (Brewer & Gaudin, 2020).

For example, a meta-analysis by Sun et al. (2019) on the Tibetan

plateau demonstrates that moderate grazing enhances native plant cover, biomass allocation, nutrient cycling, and carbon sequestration but also leads to soil compaction, erosion, reduced plant height and biomass, and shifts in plant and soil microbial communities (Sun et al., 2019). These findings highlight the need for carefully managed grazing to optimize ecosystem benefits. Long-term vegetation monitoring, combined with tracking stocking density across diverse areas, is crucial for understanding the ecological impacts of grazing management, especially in the emerging field of solar grazing. This information can help guide decision-making tools regarding the timing and intensity of grazing. Solar grazing practitioners and solar developers should embrace the complexities of solar grazing. Recognizing that, much like over 150 years of grazing management research which acknowledges the intricacies of good and bad grazing practices on ecosystem health, solar grazing also has multifaceted effects. Acknowledging these complexities will encourage science-based grazing management research to address them, benefiting both energy production and agriculture. Therefore, systematic monitoring of vegetation will be important to understand the impacts of the grazing treatments within solar systems and allow for adjustments of stocking rates and utilization to balance vegetation management, animal production, and rangeland sustainability goals (Launchbaugh et al., 1969).

3.3. Need for evaluations in native plant communities

When reviewing the available literature, and the potential concerns for native rangelands, it becomes apparent that there is a paucity of research on native plant communities and solar grazing projects. Andrew et al. (2021) assessed exotic forage pastures in Oregon grazed by weaned Polypay lambs, finding a 38 % decrease in forage production under solar. However, this decrease in forage yield maybe offset by an increase in forage quality and lower maintenance energy requirement of sheep under solar array shade when compared to lambs managed on open pastures. These study pastures were dominated by exotic forages, primarily festulolium (*X Festulolium braunii*), white clover (*Trifolium repens*), chicory (*Cichorium intybus*), and plantain (*Plantago lanceolata*). Interestingly, lamb growth rates in the spring were similar; however, lambs managed under solar consumed less water at a few time points. In a follow-up study investigating the impact of ground-mounted solar panels on herbage and sheep production across simple, diverse, and legume pastures, Andrew et al. (2024) found that pasture production efficiency was significantly reduced because of decreased light availability across all pasture types that were within or under the solar array. The greatest reduction in forage production in partially shaded areas occurred in early spring, a trend that was consistent in both years, regardless of pasture species diversity. Although forage production was slightly greater in partially shaded areas compared to open areas during the summer of 2021, the difference (~300 kg DM ha⁻¹ or less) was insufficient to compensate for the earlier reductions during the spring growing seasons. Furthermore, Hassanpour et al. (2018) assessed forage production under solar panels in Oregon, focusing on exotic species (80 % *Alopecurus* and *Agrostis*), and reported nearly double the biomass under the panels because of reduced solar radiation and increased water availability. However, the study's limitations (data collected exclusively in summer, utilizing a one-time harvest, and the absence of grazing) restricts its applicability, especially for native species within managed grazing systems. Moreover, the lack of detailed methodology and ecological context makes it difficult to apply these findings to solar grazing practices. Additional research with explicit methodologies is needed to evaluate native species under varied environmental conditions, including grazing and seasonal variations, to better identify and inform best management solar grazing practices.

Unfortunately, in additional studies provided in the literature, critical details like forage species are not provided. For instance, Madej et al. (2022) reported reduced radiation (92–94 %) under solar panels in France, with differential effects on plant growth during drought and wet

conditions. However, this study provided no information on forage species or ecological context, resulting in significant gaps in understanding and replicability. Similarly, Kampherbeek et al. (2023) reported a 147 % increase in biomass yield that was not under the solar array in a California study on “native rangeland”; while forage digestibility and protein concentrations were greater in vegetation collected from under the solar array. Again, in this case, the description of vegetation was not provided.

Knowledge gaps in research, including the emphasis on exotic forages and limited botanical details, highlight the need for more comprehensive studies. For example, while Sturchio et al. (2024a) suggest that agrivoltaics can sustain semi-arid grasslands, their study focused on pastures with predominantly exotic or invasive species such as smooth brome (*Bromus inermis*), orchard grass (*Dactylis glomerata*), alfalfa (*Medicago sativa*), and yellow salsify (*Tragopogon dubius*). This emphasizes the importance of incorporating native species and transparent methodologies in future research on livestock management within agrivoltaic systems. Furthermore, these studies raise broader questions about the impact of solar infrastructure on plant biodiversity. For instance, Graham et al. (2021) found that partial shading from solar panels delayed bloom but increased late-season floral abundance, a potential benefit for dry ecosystems. However, this area of focus alone warrants further investigation across diverse ecosystems. Additionally, future research should examine the effects on avian communities, particularly species of conservation concern such as ground-nesting birds (Gerringer et al. 2022). Addressing these gaps is crucial for a holistic understanding of the ecological implications of managing grazing systems within utility-scale solar systems.

3.4. Adaptive stocking rates feed management solutions

To highlight the challenges of drought and regional precipitation differences in solar grazing sites, consider a 12.1-hectare site in the northeastern U.S. with forage production of 3360 kg of dry matter (DM) per hectare (ha). With a 70 % utilization rate to minimize shading risks, this site can support 200 ewes with lambs for 22 days. However, under drought conditions reducing forage production by 50 % (to 1680 kg DM/ha), the same site could only sustain the same group of sheep for 11 days or support half the number of animals for the full 22 days. In contrast, a 404.7-hectare solar grazing site in a semi-arid region, producing 1344 kg DM/ha, requires different management. At a 50 % utilization rate, the site could support 1000 ewes for 90 days. During drought conditions also reducing forage production by 50 % (to 672 kg DM/ha), the stocking rate must be adjusted, either reducing the number of sheep to 500 for 90 days or maintaining 1000 ewes for just 45 days. Moreover, during wetter periods with an increase in forage production, there may be a need for more animals to manage excess forage growth during productive periods which may be more achievable in regions with larger sheep inventories, as more animals can graze excess forage. Unfortunately, in many U.S. areas with increased forage growth potential because of greater precipitation, there are insufficient sheep numbers to manage this effectively. Conversely, a significant challenge for solar grazing in semi-arid regions is securing enough harvested feed to offset shortages during drought (Salem and Smith, 2008; Whitney and Stewart, 2013). In such cases, local agricultural infrastructure plays a crucial role in supplying feedstuffs to maintain a resilient solar grazing industry. Alternatively, in temperate regions with excess forage growth but fewer sheep, harvesting forage as dry or ensiled forage could ensure future feed supplies while maintaining site vegetation. These examples demonstrate the need for adaptive management to maintain vegetative growth in utility-scale solar systems. In regions with stable precipitation, stocking rates and grazing periods are more predictable. However, in semi-arid areas, producers must adjust grazing strategies during drought to support both livestock and forage maintenance (Bocquier and González-García, 2010). Even in less arid regions, climatic variability requires both livestock producers and solar developers to align

vegetation management with animal production effectively.

3.5. Rethinking flock production calendars and matching animal to grazing resource

Adjusting flock production calendars, particularly breeding and lambing schedules, is crucial in solar grazing systems, moving away from traditional fixed production systems (NASEM, 2008; Julian et al., 2020). While logistical considerations such as labor, climatic volatility, and predation concerns factor into altering production calendars, timing grazing with optimal forage quality and quantity is essential.

In the northern plains and intermountain west, lambing in late May and June can align with peak forage digestibility, reducing the need for supplemental energy and protein. Comparatively, commercial and pasture-based lamb production in the Midwest and Eastern U.S. also tends to follow natural forage availability. However, in this system, the window of forage availability is greater, with access to quality forages commonly stretching from early spring to late fall depending upon local climatic and environmental conditions in addition to forages species and type (e.g., annual versus perennial). Regardless of location, ewes' crude protein (CP) and energy requirements increase by 83.7 % and 9.9 %, respectively, from lambing to peak lactation (20–30 days post-lambing), and then decline by 33.2 % and 20.0 %, respectively, from the first six weeks to the last six weeks of lactation. Lambs' CP and metabolizable energy (ME) requirements increase significantly with growth, doubling from 45 g to 89 g CP as they grow from 13.6 kg to 27.2 kg, while ME remains constant at 2.51 Mcal/kg. To support modest growth rates in young lambs (99.7 g/day), forage-based diets must provide approximately 11.0 % CP and 4.3 Mcal/kg ME. However, the optimal nutritive value of common cool-season grasses typically persists only 30–40 days beyond early-season biomass production (Ganskopp and Bohnert, 2001; Scasta, 2017; Kersh et al., 2024). Mixed grass prairies with diverse plant communities can extend this nutritional window (Scasta, 2017) but may still inconsistently meet lambs' energy, protein, macro-micro mineral, and vitamin requirements. In rotational grazing systems with sufficient precipitation, such as the Midwest and Eastern U.S., forage regrowth can regain early-season nutrient concentrations (Sturchio et al., 2024b), though logistical challenges may limit this strategy's effectiveness.

3.6. Managing animal growth and forage quality

During the vegetative stages of cool-season plant growth, moderate lamb performance might be maintained, but setting up creep grazing or supplemental creep feeding systems can ensure optimal lamb performance and optimal leaf-to-stem ratio of the grazing resource (Poli et al., 2020; Silva et al., 2020). In semi-arid environments, supplementation up to 250 g/day can exert a substitution effect, sparing forage resources (Bosing et al., 2014). Similarly, in more temperate regions, providing lambs with supplemental feed at a rate of 1 % live body weight reduces forage intake, lessens parasite burden, and increases lamb growth (Campbell et al., 2021). Alternatively, creep grazing allows lambs exclusive access to highly digestible, protein-rich forage or regrowth prior to the ewes. While the efficacy of this method in semi-arid unimproved pasture systems has yet to be thoroughly evaluated, this method has resulted in approximately 40 % greater growth compared to non-creep grazed lambs in an irrigated pasture system (Ates et al., 2017). This potential synergy might allow ewes to manage lesser quality biomass while lambs graze greater quality forage.

In semi-extensive and extensive systems of the Western U.S., weaning traditionally occurs around 120 days of age, while in the Eastern U.S., it often takes place at 60–90 days. For western producers, this timing typically aligns with the end of summer grazing leases, reduced forage availability and quality, or an increased supply of feeder lambs entering the market. For those producers in the east, weaning occurs at an earlier age to capitalize on lamb market premiums in the spring and general lack of quality forage availability throughout the summer grazing

season. Forage availability at solar grazing sites may offer sheep producers greater flexibility and security, particularly suited for production systems in the Midwest and Eastern U.S. that focus on forage quality in cultivated production systems. Regardless of location, producers can utilize extended grazing opportunities within solar sites to manage weaned lambs, which are at higher risk of predation, and delay marketing feeder lambs during peak periods (e.g., August to October) when prices are generally depressed because of market oversupply (Ritchie, 2022). This approach to extending lamb supply by slowing the growth of weaned lambs and delaying slaughter dates supports long-term efforts in the U.S. sheep industry to reduce the seasonality of lamb production (American Lamb Industry, 2014; Whaley et al., 2022) and reducing the need for imports to fill those production gaps.

Alternatively, producers could also move ewes to solar installations post-weaning, as their nutritional requirements are lowest during this period, making them ideal for vegetation management, including the utilization of lower-quality forage. It's crucial, however, to align vegetation management goals with each producer's production cycle. For example, ewes in the pre-breeding phase or those being bred should be moved from low-quality forage sites to optimize conception rates. If timed correctly, this environmentally induced flushing effect could be a beneficial strategy to enhance lamb production (Scaramuzzi et al., 2006).

Adapting sheep production calendars (e.g., breeding, lambing, weaning) to optimize solar grazing opportunities requires clear communication and predictable leasing arrangements among livestock owners, contract graziers, and solar developers. Climatic factors affecting animal performance and vegetation growth will increasingly rely on emerging tools that utilize historical climate data. Tools like Grass-Cast (University of Nebraska-Lincoln, 2024) for predicting forage production and the Climate Explorer (National Environmental Modeling and Analysis Center, 2024) for forecasting adverse weather conditions can aid in predicting average daily minimum and maximum temperatures for specific regions. In climatically volatile high plains ecosystems, unexpected snowfall, blizzards, or excessive rainfall events in the Midwest and Eastern U.S. can hinder grazing access, creating significant logistical challenges and public perception issues in extending the grazing season. To mitigate these weather-related disruptions, solar grazing practitioners should prioritize stockpiling feed and feeding equipment, strategically positioning shipping yards, corrals, and handling systems, and utilizing weather prediction and forecasting tools. Implementing this support infrastructure during the solar development phase, where possible, will enable graziers to achieve precision grazing management and enhance the often-transient perception of solar developers' commitment to sustainable grazing practices.

3.7. Drought, climatic variability, and forage diversity in solar grazing systems

The regional variations in forage quality and quantity are emphasized by Andrews et al. (2024) in a study from the Mediterranean climate of western Oregon. Over a two-year period, total forage biomass was reduced by 31 %, regardless of whether forage species were predominantly grasses or a mix of diverse forages, indicating a significant decrease in total DM production. This underscores the challenge that drought and climatic variability pose to forage production in solar grazing systems.

Research from Andrews et al. (2024) indicates that incorporating diverse forage mixtures with functional attributes such as shade tolerance and resistance to waterlogging is crucial for enhancing productivity and persistence within PV systems, especially under challenging microclimatic conditions. However, the establishment and persistence of these diverse forages can be problematic, particularly in regions prone to climatic extremes.

Consistency of animal performance may be a more important metric for grazing within solar systems rather than optimizing for the

introduction of specialized pasture mixes. The unique dietary preferences of sheep and the persistence challenges of some forb species may limit the effectiveness of highly specialized introduced forage mixtures in agrivoltaic systems (Evju et al., 2009; Grace et al., 2018; Gultekin et al., 2021). Nonetheless, the findings from Andrews et al. (2024) and Beck et al. (2024) highlight the importance of forage diversity for maintaining consistent lamb performance across climatically dynamic grazing systems.

4. Research needs, industry considerations, and knowledge gaps

Research on agrivoltaic grazing systems is still evolving, and there are several key areas that require further exploration to optimize these systems for both energy and livestock production. Much of the research published to date has been conducted within solar systems that tend to be small in scale; therefore, significant knowledge gaps exist and require further investigation on a much larger “megawatt” scale. However, a major challenge of conducting agrivoltaic research at utility “megawatt” scale is gaining access to a site. Beyond this initial challenge, there is a clear need for research in native and rangeland plant communities to understand how to adaptively manage the intensity and timing of sheep grazing to avoid rangeland degradation, weed invasion, and adapt to the inherent variability of precipitation that could create times of reduced or excessive forage biomass depending upon climatic and environmental conditions.

Overall, optimization studies involving engineering design, agronomic practices, and economic considerations are essential to improving the efficiency of land use in agrivoltaic systems. Economic modeling of agrivoltaic grazing systems is another important research need, including analysis of combined revenue from energy production, livestock, and potential ecosystem services like carbon sequestration or enhanced biodiversity. Furthermore, understanding the effects of solar panel shading on pasture establishment, forage quality and growth is essential, as agrivoltaics-specific microclimatic changes affect pasture establishment and persistence greatly. Studies on specific agronomic practices, particularly in the areas beneath solar panels, can help improve forage productivity and grazing outcomes. Agrivoltaics specific grazing systems research is particularly crucial to understand how to best utilize these spaces and the effect of solar panels on animal production, health, behavior, as well as wildlife interactions. Additionally, understanding how managed grazing impacts wildlife corridors and biodiversity in agrivoltaic systems is important for balancing livestock production with conservation goals. In short, long-term studies should focus on ecosystem services such as soil moisture retention, carbon sequestration, and biodiversity enhancement. Sociocultural and policy research can help overcome barriers to adoption by developing frameworks that encourage the integration of agrivoltaic systems, benefiting both renewable energy and sustainable livestock management.

4.1. Solar site accommodations for grazing success

Solar developments with a grazing strategy in the planning and development stage offer a unique opportunity for graziers to operate more efficiently. Gate placement, water access, and forage species establishment are a few categories that create significant improvement to long term grazing feasibility and success. Utility-scale sites cover significant acreage, often spread over multiple sections that can be both contiguous and non-contiguous. Identifying a pathway or flow of rotating a sheep flock from one area to the next may involve additional points of entry across multiple tracks of land that may or may not be fenced. These additional access points create an additional cost to the construction phase but offer long term benefits to graziers. Likewise, access to water onsite provides significant benefit to a grazing enterprise. Water access can be provided in a multitude of forms depending on region. Underground well drilling, public water access (*i.e.*, municipality) and retention ponds provide onsite water, greatly reducing labor

and cost of the grazing operation. This commitment for a grazing initiative also increases cost of development; however, the long-term saving in vegetation management contract can be a source of justification. Additionally, from an owner/operator perspective, a permanent water supply is beneficial in the event panel washing is required to remove dirt or debris from the panel face.

4.2. Technical and design issues

The integration of PV panels into agricultural settings introduces significant technical challenges. Toledo and Scognamiglio (2021) and Trommsdorff et al. (2021) highlighted that not all PV panel designs are suitable for livestock grazing (*e.g.*, cattle), particularly those with low clearance (1–3 m), which can impede access for tractors and other agronomic pieces of equipment (*e.g.*, seeders, mowers, etc.). The complexity and cost of installation increases when panels must be elevated to accommodate for agricultural machinery or larger livestock. Moreover, the need to balance adequate sunlight for crops while optimizing energy production complicates the design process. This underscores the necessity for developing new technologies and designs that facilitate better integration of livestock and agronomic crop production with PV systems. Ultimately, the optimal panel configuration in agrivoltaics will depend upon the production priorities (*e.g.*, energy, food, water) or long-term use coupled with economic considerations. Proctor (2022) estimated in an agro-economic modeling that to maintain a positive net present value over a 20-year period, racking costs must be less than \$0.50/W, making panel heights above 2.44 m an economically unviable option in most regions of the U.S. Therefore, in order to promote and support the use of utility-scale solar facilities in the area of agrivoltaics and especially vegetation management strategies that utilize sheep, developers and engineers must be willing to consider the future applications of these sites. Prior to placing piles in the ground, factors such as panel spacing, water infrastructure, and grazing infrastructure design should be at the forefront of these initial construction discussions.

4.3. Microclimatic conditions

The microclimatic conditions created by PV panels significantly impact crop growth (Sturchio et al., 2024b). Solar panels may create a decoupling effect between the timing of optimal soil temperature and moisture availability, causing poor germination and establishment of pastures. In fall, panels can block rainfall from reaching the soil beneath them, leading to dry conditions during the crucial early germination period. Later in the season, when water finally reaches these areas, soil temperatures may be too low for optimal germination. While shading can reduce water evaporation, it also limits light availability, potentially hindering pasture establishment and forage growth. Lesser light availability under solar panels or in partially shaded areas may be compensated by greater plant water potential during periods of water scarcity in arid and semi-arid regions (Sturchio et al., 2024a). However, it is important to note that in the fall, the panels can block rainfall from reaching the soil beneath, delaying the soil’s return to full moisture capacity. This delay often occurs when air and soil temperatures have already dropped to suboptimal levels for germination and plant growth, leading to a temperature-water uncoupling that hinders production. In regions with heavy rainfall and poor soil drainage, the accumulation of excess water at the edges of panels can lead to waterlogging, further complicating forage production within PV facilities (Andrew et al., 2024). Additionally, prior land-use pre-construction should also be heavily considered. Within traditional row crop tracks of land, drainage tile may have been put in place to improve soil drainage. During construction, drainage tile damage may occur, thus leading to saturated soil conditions resulting in poor forage establishment and longevity.

4.4. Wildlife and plant biodiversity

The conversion of pastoral and agricultural landscapes to agrivoltaic sites significantly impacts crop and livestock production, as well as wildlife and biodiversity at both landscape and microhabitat levels. At the landscape scale, medium and large-scale PV installations may cause habitat loss and fragmentation while at the microhabitat scale, PV panels alter the microclimatic and habitat conditions (Gómez-Catasús et al., 2024). Agrivoltaics sites can disrupt local ecosystems but also create environments that might support both grazing livestock and wildlife habitation. Kampherbeek et al. (2023) observed that fencing around solar sites can protect certain wildlife, such as rodents, from predators, potentially altering local biodiversity and ecosystem dynamics. These sites could also serve as areas for developing "conservoltaic systems," which combine solar energy production with biodiversity conservation to support wildlife and pollinators (Graham et al., 2021; Blaydes et al., 2022; Nordberg and Schwarzkopf, 2023). However, the interaction between grazing sheep and wildlife in agrivoltaic systems remains largely unexplored. This lack of research creates significant gaps in understanding how these animals coexist and influence each other within these environments, as well as how to manage these interactions to balance agricultural productivity with ecological conservation. Long-term studies are critical to understand the impacts of agrivoltaic grazing systems on soil health, crop productivity, and ecosystem services.

In terms of invasive species and weeds, shading from PV panels can favor the growth of shade-tolerant weeds, complicating weed management strategies in agrivoltaic systems. Mechanical weeding is challenging around PV infrastructure, necessitating the development of new management approaches to prevent the spread of invasive species (Andrew et al., 2024). Regrettably, there is little to no published data that evaluates the impact on non-target species plant growth and their prevalence or lack thereof within and around solar arrays. Therefore, additional research as it relates to invasive and weed management as well as its control within these solar sites is of great importance.

4.5. Animal behavior, health, welfare, and operational challenges

Photovoltaic panels can provide beneficial shade for livestock, particularly in hot climates (Sharpe et al., 2021; Fonseca et al., 2023), but panels also alter grazing behavior (Andrew et al. 2021; Kampherbeek et al., 2023). Andrew et al. (2021) has shown that sheep tend to graze and rest predominantly under the panels, leading to increased trampling and nutrient distribution specifically under the solar array, which can negatively affect forage production and nutrient distribution. Kampherbeek et al. (2023) also observed that sheep with access to solar panels spent more time grazing each day compared to those on native rangeland, although this was partly because of the reduced forage availability in pastures within solar sites.

Management of gastrointestinal nematode (GIN) parasites in a solar grazing system could be an issue for several reasons. Generally, GIN are more prevalent on predominantly grass pastures with adequate moisture and warmer temperatures, and raise greater concern when sheep are continuously rather than rotationally grazed (Burke and Miller, 2020). Lambs are more susceptible to GIN than adults in maintenance phase of production because their immune system has not fully matured. In the southeastern U.S. and much of the eastern and Midwestern U.S., *Haemonchus contortus* will be the predominant GIN which is a blood feeder and can cause anemia in highly susceptible lambs or sheep that are in poor condition. Because anthelmintic resistance is highly prevalent globally, dewormers will not be a reliable preventative or control measure (Burke and Miller, 2020). Graziers will need to be cognizant of risks of these parasites and have a plan to treat animals when needed.

Managing the dual-use nature of solar grazing requires careful coordination between energy production and livestock farming. Bowen (2024) discussed the operational difficulties, including the need for

specialized training and the challenge of maintaining PV panels, crops, and livestock simultaneously. The fragmented nature of grazing areas within these systems further complicates management, emphasizing the need for adaptive strategies to optimize land use and forage availability. Addressing these challenges also highlights an opportunity for Extension outreach programs. Given that many solar graziers may be newcomers to the sheep industry, there is a clear need for education on basic husbandry practices. Extension specialists and educators can play a critical role by tailoring programs to meet the unique needs of solar grazing stakeholders, bridging knowledge gaps, and working with practitioners to guide applied research and outreach efforts. By addressing both the basic and specialized aspects of solar grazing, Extension programs can better support the sustainability and success of these dual and multi-use systems.

4.6. Economic, financial, social, and regulatory limitations

The economic viability of solar grazing systems is influenced by various factors, including crop types, local energy prices, and available subsidies. While agrivoltaic systems can offer financial benefits, particularly for ruminant livestock producers, the initial investment is substantial, and fluctuations in energy and agricultural markets add uncertainty. Additionally, the costs associated with panel removal, waste management, and land remediation at the end of the panels' life cycle can be significant (Bowen, 2024; Brent et al., 2023).

The implementation of agrivoltaic systems often faces regulatory and social obstacles as well. Existing regulations may not be well-suited for these systems, complicating the permitting process. There may also be resistance from local community members concerned about land use changes or the esthetics of PV installations. Agir et al. (2023) and Brent et al. (2023) emphasized the need for Extension services and educational programs to help community members, farmers, and energy developers navigate these challenges and effectively design and manage agrivoltaic systems to meet the needs and interests of all parties involved. These challenges highlight the need for further research and development to optimize solar grazing practices and ensure their sustainability and economic viability.

4.7. Sheep industry infrastructure concerns

The growth of the solar grazing industry is expected to lead to an increase in sheep inventory, particularly in regions where sheep numbers have historically been low. This reversal of the declining trend will necessitate adaptations in allied industries such as nutrition, pharmaceuticals, handling equipment, marketing services, and commercial abattoirs. Historically, the American sheep industry has been considered minor by some private sectors, leading to limited research and development in areas like combination anthelmintics, vaccine development, and feed additives. The expansion driven by solar grazing could serve as a catalyst for accelerating research, development, and regulatory approvals in these areas.

A critical concern, however, is the potential strain on sheep marketing and abattoir services. Market saturation in regions with limited outlets may require better coordination, especially outside peak periods when sheep are in high demand for vegetation control (Kochendoerfer and Thonney, 2021). The greatest sheep industry harvest capacity is found in larger commercial plants in the Western U.S. (CA, CO, TX), with medium-sized plants located in the Great Lakes region (MI, WI). Although these plants, built during times of larger U.S. sheep inventory numbers, are not currently operating at full capacity, Additionally, the distance between large solar grazing sites and major packing plants currently poses as a challenge. Coordination with traditional lamb commodity infrastructure, such as lamb feedlots and abattoirs, will be essential to ensure that lambs are marketed and harvested efficiently, ultimately increasing consumer demand for U.S. lamb.

Table 1

Comparison of the top 5 states with the greatest concentration of solar installation capacity and the top 5 sheep producing states based upon total breeding sheep numbers.

Solar capacity installation 2023	Gigawatts installed in 2023 ¹	US Ewe inventory 2024	Total breeding sheep ²
1. Texas	6.5	1. Texas	515,000
2. California	6.2	2. California	270,000
3. Florida	3.2	3. Wyoming	245,000
4. Colorado	1.6	4. Utah	240,000
5. Ohio	1.3	5. Colorado	190,000
Total U.S.	32.4	Total U.S.	5,030,000

Solar Energy Industries Association (SEIA, 2024)
USDA NASS, 2024

5. Conclusion

As the interest in utility-scale solar development increases, exploring the feasibility of dual and multi-use land management strategies that incorporate agricultural and conservation practices with solar energy production are of growing interest. Solar grazing systems present a promising approach to enhance both forage quality and yield while subsequently improving livestock performance. By aligning forage availability with the nutritional demands of sheep or other livestock while integrating adaptive management strategies to cope with climatic and environmental variability, these systems can contribute to more sustainable and resilient livestock production. However, it will be critical for the American sheep industry and its associated partners to support the increase in sheep and lamb inventory numbers across the nation needed for vegetation management and solar grazing needs. Further research and regional adaptation are essential to optimize these systems for diverse environmental conditions. (Table 1)

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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