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The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons From the InSPIRE Research Study

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Glossary and Acronyms

ARDEC	Agricultural Research, Development, and Education Center
ASTRO	Agriculture and Solar Together: Research and Opportunities
BWSR	Board of Water and Soil Resources
CdTe	cadmium telluride
DOE	U.S. Department of Energy
InSPIRE	Innovative Solar Practices Integrated with Rural Economies and Ecosystems
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
MNL	Minnesota Native Landscapes
NCAT	National Center for Appropriate Technology
O&M	operations and maintenance
PAR	photosynthetically active radiation
PGP	Prescribed Grazing Plan
PV	photovoltaic
PV-SMaRT	Photovoltaic Stormwater Management Research and Testing
NREL	National Renewable Energy Laboratory
USDA	U.S. Department of Agriculture

Executive Summary

The concept of agrivoltaics (combining agriculture and solar photovoltaic technologies on the same land in novel configurations) has emerged as an approach to mitigate conflicts between solar and agricultural activities by providing mutual benefits and added value to each sector.

The U.S. Department of Energy (DOE) has supported agrivoltaics research since 2015 through its Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE) research project (National Renewable Energy Laboratory 2022). The InSPIRE project is the most comprehensive coordinated research effort on agrivoltaics in the United States. The project has examined opportunities and trade-offs at over 25 sites across the country that span crop production, pollinator habitat, ecosystem services, and livestock production.

Integrating research activities with active commercial agricultural operations can introduce unique challenges for both researchers and site operators. This synthesis report highlights both technical and nontechnical insights from the InSPIRE agrivoltaic field research sites from 2015–2021 to support (i) appropriate deployment of agrivoltaic projects, (ii) more successful agrivoltaics research, and (iii) more effective partnerships on agrivoltaic projects.

The lessons discussed here are focused less on specific case study outcomes (i.e., the percent change in crop yield in an agrivoltaics configuration) and more on the elements that enable agrivoltaics projects to be installed and operated and the factors that facilitate research at those sites. We find that there are some insights that are applicable across all types of agrivoltaic projects, whereas ecosystem service projects and crop production agrivoltaic projects often have other unique considerations.

Lessons learned are categorized into five primary themes, termed “The 5 Cs” (Figure ES-1):

- **Climate**, Soil, and Environmental Conditions (C1): *The ambient conditions and factors of the specific location that are beyond the control of the solar owners, solar operators, agrivoltaic practitioners, and researchers.*
- **Configurations**, Solar Technologies, and Designs (C2): *The choice of solar technology, the site layout, and other infrastructure that can affect light availability and solar generation.*
- **Crop Selection and Cultivation** Methods, Seed and Vegetation Designs, and Management Approaches (C3): *The methods, vegetation, and agricultural approaches used for agrivoltaic activities and research.*
- **Compatibility** and Flexibility (C4): *The compatibility of the solar technology design and configuration with the competing needs of the solar owners, solar operators, agricultural practitioners, and researchers.*
- **Collaboration** and Partnerships (C5): *Understandings and agreements made across stakeholders and sectors to support agrivoltaic installations and research, including community engagement, permitting, and legal agreements.*

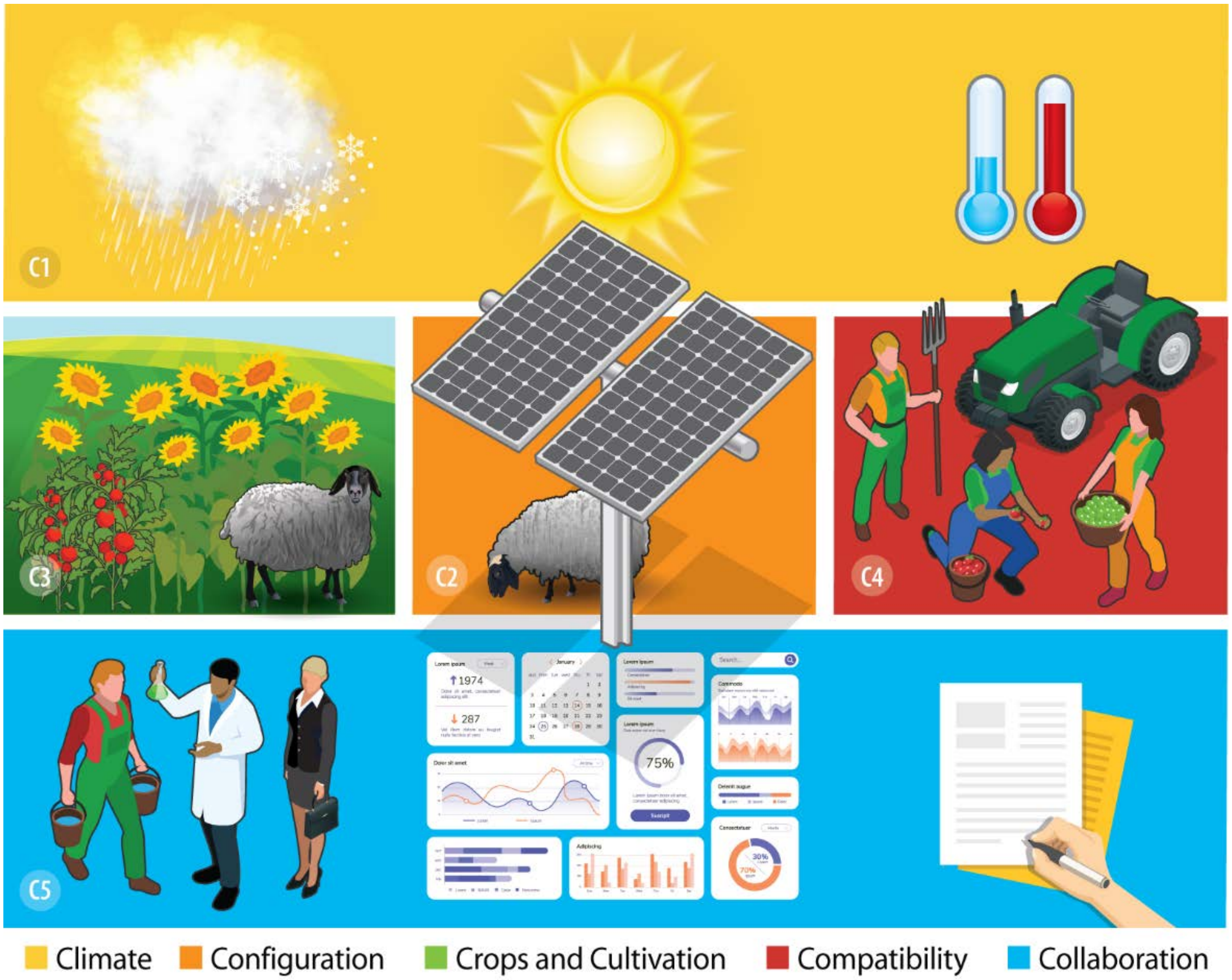

Figure ES-1. The 5 Cs of agrivoltaic project success.

Each of the 5 C categories has multiple determinants that can lead to success in agrivoltaic projects and/or research. The full list is shown in Table ES-1.

Table ES-1. 5 C Agrivoltaic Project Success Determinants

Category	Project Determinant	Agrivoltaics Type
C1: Climate, Soil, and Environment	Soil Quality	All
	Ambient Climate	All
	Prior and Surrounding Land Uses	All
	Water Access	All
	Pests and Disease	Crop/Livestock
C1 Research Considerations	Representativeness and Suitability	All
	Nearby Land-Use Change	All

Category	Project Determinant	Agrivoltaics Type
C2: Configurations, Solar Technologies, and Designs	Project Capacity	All
	Panel Height	All
	Racking System	All
	Panel Spacing	All
	Row Spacing	All
	Photovoltaic Technology	All
C2 Research Considerations	Project Land Area	All
C3: Cultivation Methods, Crop Selection, and Management Approaches	Vegetation Selection	All
	Vegetation Establishment Methods	Ecosystem
	Markets and Distribution	Crop/Livestock
C3 Research Considerations	Research Plot Size	All
	Research Duration	All
	Complementary Modeling and Validation	All
	Control Plot Design	All
	Established Research Methods	All
	Common Metrics	All
C4: Compatibility and Flexibility	Sitewide O&M Plans	All
	Infrastructure Placement	Crop/Livestock
	Farm Practice Compatibility	Crop/Livestock
	Prescribed Grazing Plans	Crop/Livestock
C4 Research Considerations	Researcher Access	All
	Proximity of Site	All
	Installed Research Equipment	All
	Data Collection Compatibility	All
	Crop Rotation Planning	All
C5: Collaboration and Partnerships	Understanding Multiple Priorities and Establishing Common Goals	All
	Clear Roles and Responsibilities	All
	Information Sharing	All
	Long-Term Ownership and Personnel Consistency	All
	Groundcover Compromises	All
	Farmer Bandwidth	Crop/Livestock
	Community and Stakeholder Engagement	All
	Planning, Permitting, and Zoning	All
C5 Research Considerations	Communication and Signage	All
	Cross-Trained Personnel	All

We conclude with 10 specific recommendations to encourage more successful agrivoltaics projects and more productive research activities going forward. These activities align with the 5 Cs and include:

1. **Developing innovative solar technology designs and configurations**: Expanding agrivoltaic field research to consider additional novel PV technologies and configurations will improve our understanding of agrivoltaic benefits and trade-offs.

2. **Adopting compatible, flexible, and iterative research approaches**: Solar project designs that include accommodations for agrivoltaic activities and research from the beginning can be more successful in facilitating the success of both.

3. **Standardizing research methods and agrivoltaics approaches**: Common and universally accepted research protocols enable better science and more opportunities for collaboration, data sharing, and transferable insights. Meanwhile, developing and adopting standard protocols across agrivoltaic research sites can further these aims.

4. **Establishing effective and mutually beneficial partnerships**: It is essential to establish priorities, common goals, roles and responsibilities, communication norms, and contingency plans at the start of project and research development.

5. **Conducting long-term field studies**: Outcomes from long-term sites will improve investment and design decisions on new sites.

6. **Intensifying collaborative multi-sector research**: Agrivoltaic projects can likely include research activities from multiple sectors, enabling more comprehensive research.

7. **Expanding the geographic diversity of agrivoltaics**: New projects in more locations can help create new data sets and better understanding of agrivoltaic trade-offs while also helping to validate agrivoltaic models.

8. **Generalizing from site-specific to broad outcomes**: Collaborative efforts can focus on appropriately combining and comparing results to obtain more generalized information applicable across regions and vegetation types.

9. **Sharing data nationally and internationally**: Creating shared data platforms and resources that developers, practitioners, and researchers can access will help accelerate research outcomes, deployment decisions, and investments.

10. **Prioritizing diversity, equity, and inclusion in research and partnerships**: Engaging diverse audiences will enable additional perspectives, innovations, and applications of agrivoltaics that are tailored to communities that could directly benefit from agrivoltaic advances.

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1 Introduction

Solar energy deployment in the United States is rapidly increasing, with over 20 GWdc of capacity added in 2021 (Solar Energy Industries Association (SEIA) 2021). Solar photovoltaic (PV) technologies make up the majority of solar energy projects. PV technologies can be deployed on rooftops, or they can be ground-mounted (U.S. Department of Energy 2021). Ground-mounted installations require 3–10 acres per MWdc of installed capacity (Ong et al. 2013; Bolinger and Bolinger 2022). Utility-scale PV installations are expected to require a minimum of 4 million acres, and up to 11 million acres of land, by 2050 based on solar deployment scenarios (U.S. Department of Energy 2021). Agricultural lands coincide with areas favorable to solar energy deployment; the available solar insolation and stable soil conditions on agricultural lands reduce project risks (Adeh et al. 2019). Farmlands have many characteristics that make them desirable from a solar development perspective, including having existing connections to the electric grid, access roads, and relatively flat ground. These characteristics, combined with the growing economic challenges of traditional farming, have led to solar projects being developed on agricultural lands (Walston et al. 2021). Deployment of solar technologies in rural landscapes has led to community resistance to solar development, similar to the resistance to cellular tower development, wind energy development and oil and gas development (Wilke 2020; Petrova 2013; Thomas et al. 2017; Moore et al. 2021) in some locations throughout the United States.

The concept of agrivoltaics (combining agriculture and solar PV technologies on the same land in novel configurations) has emerged as an approach to mitigate conflicts between solar and agricultural activities by providing mutual benefits and added value to each sector (Dupraz et al. 2011; Barron-Gafford et al. 2019; Mamun et al. 2022; Goetzberger and Zastrow 1982). Given the right conditions and configurations, agrivoltaic installations have the potential to (i) improve economic viability of activities for landowners, agricultural entities, and solar developers; (ii) provide beneficial ecological services; and (iii) expand siting opportunities for solar deployment (Hernandez et al. 2019). However, in some regions and at this early stage of design maturity, agrivoltaic installations can also contribute to higher installed and operational costs, increased design complexity, and environmental trade-offs even while mitigating public opposition. Additional research is needed to assess the optimum conditions for mutual benefit across the energy and agricultural sectors (Hernandez et al. 2014; Horowitz et al. 2020). Across the globe, researchers are examining key agrivoltaic research questions, including but not limited to factors related to: vegetation establishment and growth, soil characteristics, microclimate conditions, hydrology, ecological services, and solar technology cost and performance (Agrivoltaics International Conference 2021). In some cases, these field research sites are on or adjacent to land with ongoing large-scale commercial agricultural activities, as compared to small-scale pilot-sized research sites without commercial operations. This ongoing research is helping inform regional decision-making and policies in multiple U.S. states as well as in various countries.

The U.S. Department of Energy (DOE) has supported agrivoltaics research since 2015 through its Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE[1]) research project (National Renewable Energy Laboratory 2022). The InSPIRE project is the most comprehensive coordinated research effort in agrivoltaics in the United States, and has examined opportunities and trade-offs at over 25 sites across the country that span crop production, pollinator habitat, ecosystem services, animal husbandry, and solar greenhouse systems. The InSPIRE project utilizes consistent, coordinated methods and protocols across sites to facilitate (1) data sharing, (2) more reproducible and replicable results, and (3) more rapid learning throughout the industry. Working across a diversity of sites, PV configurations, agricultural activities, and regions, the InSPIRE project offers unique insights into the elements that support successful agrivoltaic research projects.

Integrating research sites with active commercial agricultural operations can introduce unique challenges for conducting research. This synthesis highlights the technical and nontechnical insights from the InSPIRE agrivoltaic field research sites from 2015–2021 to support (i) appropriate deployment of agrivoltaic projects; (ii) more successful agrivoltaics research; and (iii) more effective partnerships on agrivoltaic projects.

[1] InSPIRE's acronym has evolved due to changes in research and development needs; the original version was Innovative Site Preparation and Impact Reductions on the Environment.

2 Agrivoltaics Research Background

Agrivoltaics is an emerging field of development in which industry-standard definitions and designs are still lacking in most states and countries. Agrivoltaics is sometimes referred to as “dual use,” “co-location,” “agri-PV,” “agri-solar,” “solar sharing,” “pollinator-friendly solar,” or other similar phrases in different parts of the world and for different applications. This section provides a brief description of agrivoltaics and the InSPIRE research project.

2.1 Definitions and Categories of Agrivoltaics

2.1.1 Agrivoltaics Definition

Agrivoltaics is defined as a land use configuration where solar energy generation and sunlight-dependent agricultural activities are directly integrated and there is a layer of agricultural productivity within the boundaries of the solar infrastructure. The hallmark characteristic of agrivoltaics is thus the sharing of sunlight between the two energy conversion systems: photovoltaics and photosynthesis. Agricultural activities include practices that satisfy human food, fiber, and fuel needs as well as activities that enhance environmental quality and the natural resource base upon which the agricultural economy depends (adapted from the U.S. Department of Agriculture (USDA)) (U.S. Department of Agriculture 2007). To date, agrivoltaics in the United States has included crop production, livestock grazing, apiary management, and other activities that intentionally involve the provision of ecosystem services (e.g., habitat creation, support for beneficial pollinating and predatory insects, native vegetation restoration, or cover cropping for soil health benefits and carbon sequestration).

It is important to note that not all PV installations on farms can be considered agrivoltaics. An essential component of an agrivoltaics system is that the solar and agricultural activities have an influence on each other. Therefore, installing rooftop PV on a barn, where there is no direct impact of the PV system on the vegetation, soil, or livestock, would not be considered an agrivoltaic project. Similarly, conventional ground-mounted solar infrastructure adjacent to agricultural land with no direct vegetation, soil, or livestock integration would not be considered an agrivoltaic project. Moreover, simply using electricity from a solar installation to power farm-related activities is not considered agrivoltaics. However, there can still be value in on-farm production and usage of solar energy outside of agrivoltaics. Solar Power Europe has proposed to specifically designate the term *agrisolar*[2] as a broader umbrella term that can encompass agrivoltaics as well as non-agrivoltaic solar energy on agricultural properties.

2.1.2 Agrivoltaics Configurations

Agrivoltaic PV configurations can be broadly split into two categories: elevated and inter-row. Inspired by agroforestry as well as the greenhouses and polytunnels of protected horticulture, elevated systems feature PV modules sited directly above the vegetation. These heights are generally greater than 6 feet (1.8 meters). The modules can act as a protective barrier against inclement weather, although there can be more substantial shading and reductions in sunlight. It is

[2] https://www.solarpowereurope.org/insights/thematic-reports/agrisolar-best-practice-guidelines

common to find higher-value crops, such as berries, grapes, short-stature fruit trees, and delicate vegetables, in elevated agrivoltaic systems.

In inter-row agrivoltaic systems, vegetation is primarily grown in between rows of PV arrays rather than directly under them. To accommodate large farming machinery, the inter-row spacing of the PV arrays can be wider than conventional ground-mounted utility-scale PV projects. Compared to elevated agrivoltaic systems, the PV modules in inter-row agrivoltaics provide less physical protection against the elements, though more sun is usually available to the vegetation. It is more common to find lower-value crops, such as grasses, grains, and hardy vegetables, in inter-row systems, and higher-value horticultural and specialty crops in elevated systems.

Of course, some overlap exists between these two broad categories, such as the example of agrivoltaic grazing operations in which ruminants graze on grass grown both below and between PV rows. Furthermore, the PV arrays may be slightly elevated to allow sheep to pass under the panels or to accommodate taller vegetation growth.

2.1.3 Agrivoltaics Categories

Agrivoltaic applications include (1) crop and food production, (2) livestock production, (3) provision of ecosystem services through vegetation management, and (4) solar greenhouses (Figure 1). These applications are not mutually exclusive, and multiple activities can occur simultaneously on a given site, including in the same area within that site at different times of year. Some projects include separated zones where crop production or ecosystem service production occurs, whereas other projects use the same zones for different purposes, such as targeted grazing in pollinator habitat zones to strategically manage vegetation at certain times of the year. It should be noted that agrivoltaic and ecovoltaic projects are not mutually exclusive.

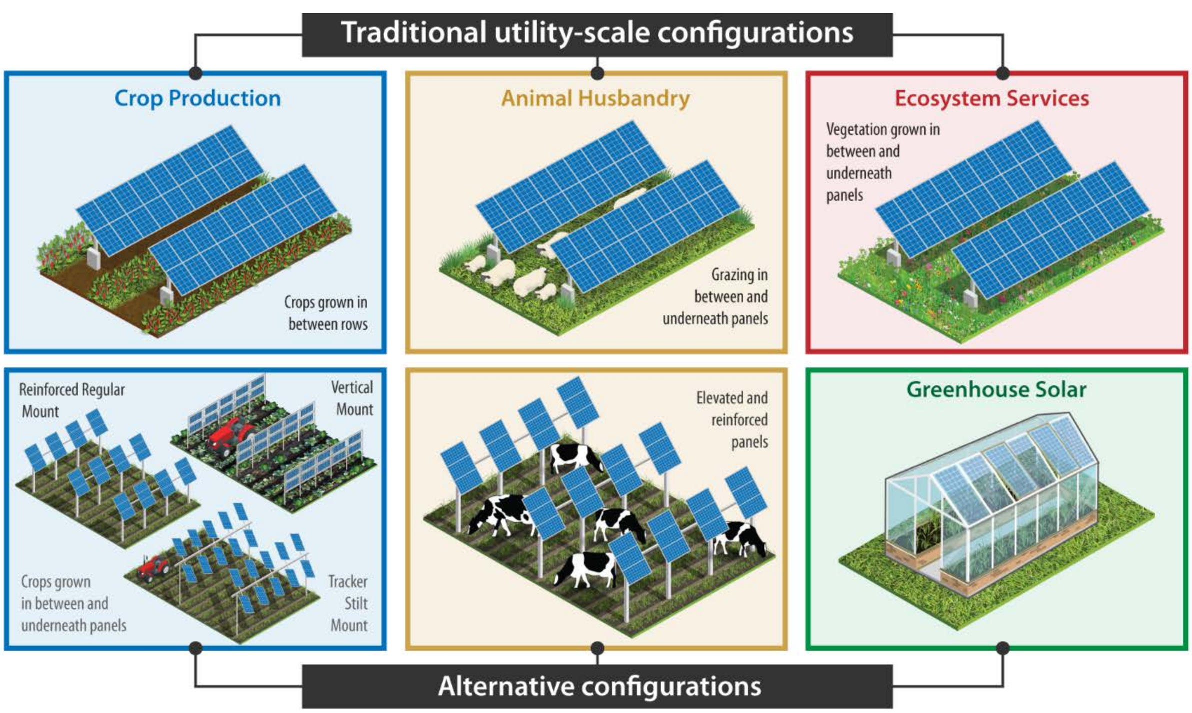


Figure 1. Types of agrivoltaics systems that have been deployed commercially.

Crop production systems include the cultivation of annual and perennial food, fiber, or specialty crops underneath and around solar infrastructure (Mamun et al. 2022; Trommsdorff et al. 2021; Marrou et al. 2013; Weselek et al. 2021; Barron-Gafford et al. 2019; Jo et al. 2022; Valle et al. 2017). Crop production systems are affected by the partial shade of solar infrastructure; crops can be grown directly underneath panels and in between rows of panels. Crops can be managed manually or with mechanized equipment. Crop production can occur within a traditional ground-mounted solar installation, or the infrastructure can be modified in terms of panel height, panel spacing, row spacing, or other aspects of design to facilitate changes in sunlight/shading patterns and compatibility with farming operations (Zainol Abidin, Mahyuddin, and Mohd Zainuri 2021). Novel technologies and configurations are being explored to support different types of crops and horticulture, including systems for orchards, viticulture, field crops, and other fruits (Riaz et al. 2021; Tahir and Butt 2022; Gorjian et al. 2022; Agostini, Colauzzi, and Amaducci 2021).

Livestock and animal husbandry agrivoltaics systems include the grazing and management of animals underneath, around, and directly adjacent to solar infrastructure. We found that researchers and practitioners have implemented agrivoltaic systems mostly with sheep, cattle, poultry, honeybees, and rabbits, although other animal operations are also possible (Sharpe et al. 2021; Pascaris, Handler, et al. 2021; Maia et al. 2020; Andrew et al. 2021). Animals can be on-site year-round, seasonally, or on an as-needed basis, as determined by the animal manager and the needs of the solar site. Animals might not obtain all of their nutrition from resources on-site, and they can be moved periodically or receive nutrition from off-site sources as a supplement. An emerging application includes the integration of solar infrastructure with aquaculture activities, although not every country includes this as an agrivoltaics category (Vo et al. 2021). In many cases, traditional utility-scale solar infrastructure does not need to be modified significantly to support livestock grazing and animal husbandry activities, but other alterations in site design—related to vegetation planting and management, fencing, water supply, and animal access—can be included to facilitate compatibility with animal husbandry practices.

Ecosystem service agrivoltaic projects encompass installations that are designed to create or restore habitat, improve soil, and provide other ecosystem services (Walston et al. 2021; Graham et al. 2021; Armstrong, Ostle, and Whitaker 2016; Walston et al. 2018). Ecosystem services can include supporting, provisioning, regulating, and sociocultural services, as shown in Table 1.

Table 1. Ecosystem Services Examples

Adapted from (U.S. Department of Agriculture n.d.)

Category	Ecosystem Services Examples
Supporting	Soil formation, photosynthesis, biodiversity
Provisioning	Clean water, food, other useful plants (e.g., timber, fiber)
Regulating	Carbon sequestration, flood control, temperature regulation
Cultural	Recreational, aesthetic, and spiritual benefits (e.g., tourism)

Habitat can support beneficial insects (e.g., pollinators, crop pest predators), birds, reptiles, mammals, or other wildlife species of interest. These sites generally require little modification of traditional utility-scale solar designs, but elevation of panel heights to a sufficient level to allow vegetation establishment of selected beneficial seed mixes is an important determinant of the potential of these sites to provide relevant services.

Solar greenhouse agrivoltaic projects include greenhouse arrangements where PV technologies are installed above or integrated with the greenhouse infrastructure to provide partial shade and light modulation (Cossu et al. 2014; 2017; 2016; Marucci and Cappuccini 2016). Solar technologies and configurations can include transparent, semi-transparent, or opaque modules resting atop or integrated with the building structure to provide changes in light availability and quality throughout the day. As with ecosystem service projects, some countries do not recognize solar greenhouses as agrivoltaics projects.

2.1.4 International Definitions of Agrivoltaics

In many other countries' definitions of agrivoltaics, "ecosystem services" projects do not qualify as agrivoltaics or they have a nuanced categorization to reflect their valuable but often indirect impacts on food production for humans. There can be ambiguity over the utilization of ecosystem services as well as whether long-term goals of improving soil conditions for a return to agricultural use after the life of the PV facility will come to fruition. In some cases, these projects could serve more of a role for wildlife preservation than agriculture. We include ecosystem services under the broad umbrella of agrivoltaics due to their ability to directly support improved agricultural activities on-site as well as their indirect impacts on adjacent agriculture.

Many countries have begun publishing formal definitions of agrivoltaics alongside policies designed to facilitate deployment of agrivoltaics. Reflecting ambiguities in definitions and categories of agrivoltaics discussed above along with regional variations, these standards are tailored to country-specific agricultural sectors and priorities, resulting in different qualification thresholds for what constitutes agrivoltaics. For example, the first legislation in Europe appeared in 2021 in the form of Germany's DIN SPEC 91434,[3] which distinguishes between elevated and inter-row systems as "categories 1 and 2," respectively, while also stating that crop yields in agrivoltaic systems must reach at least 66% of reference yields without solar. In contrast, France's independent certification group, the French Standardization Association (AFNOR), published their "Agrivoltaic Project Label: Standards for the Labeling of Class A Crop Projects"[4] in 2021, in which a minimum of 80% of reference yields must be shown to obtain a "Class A" (typically elevated) agrivoltaics project certification. In 2022, Italy published "Guidelines for The Design, Construction and Operation of Agrovoltaic Plants,"[5] which states that the land area devoted to agricultural activities within an agrivoltaics system must be at least 70% of the total area of the solar installation. Other nations are expected to publish their own agrivoltaic criteria in coming years, which could lead to additional sets of standards whereby an agrivoltaics project in one country might not qualify as an agrivoltaic project in another country. Coordinated global efforts to standardize definitions of agrivoltaics could provide greater

[3] https://www.beuth.de/en/technical-rule/din-spec-91434/337886742
[4] https://telechargement-afnor.org/certification-referentiel-label-projet-agrivoltaique
[5] https://www.pv-magazine.com/2022/07/05/italy-publishes-new-national-guidelines-for-agrovoltaic-plants/

certainty to agrivoltaic developers and practitioners, but such efforts are inherently complicated by regional variations and priorities.

2.1.5 Successful Agrivoltaic Projects

Throughout the study, we define a "successful" agrivoltaic installation as one where partners willingly conduct agricultural and ecosystem service production activities over multiple years without any long-term disruptions or impacts to the solar infrastructure or agricultural activities. Success in agrivoltaics research is defined as being able to collect sufficient data to support peer-reviewed scientific publications and to inform future agrivoltaic installations. In many cases, the success of research is dependent on the overall success of the installation, which in turn depends on effective partnerships and communication across parties. We define success in agrivoltaic partnerships as all parties having well defined roles, clear expectations, and sufficient communication pathways to ensure continual operation of agrivoltaic activities.

2.2 InSPIRE Study Background

DOE's InSPIRE project was initiated in 2015 to provide foundational information to researchers, government, the solar industry, and agricultural practitioners regarding the potential of low environmental impact solar development approaches, including agrivoltaics. The InSPIRE project has involved collaborative research among DOE national laboratory researchers; academia; agricultural practitioners; solar industry developers; electricity buyers, including electric utilities; ecological and habitat restoration companies; and nonprofit organizations. Research has focused on field-based studies that are complemented by analytical studies and public dissemination of data that can support improved decision-making. The InSPIRE project is the most comprehensive coordinated research effort on agrivoltaics in the United States, and it contains the longest continuous agrivoltaic research sites.

The InSPIRE project has conducted field research on opportunities and trade-offs at sites in 11 states, plus Washington, D.C., and Puerto Rico, that span (a) crop production, (b) ecosystem services, (c) grazing, and (d) solar greenhouses (Figure 2). The InSPIRE project utilizes consistent, coordinated methods and protocols across sites. Field-based research at agrivoltaics sites has evaluated topics such as native vegetation growth, insect populations, microclimate conditions, PV system performance, extreme weather/disaster-hardened designs, ecosystem services provisioning and wildlife monitoring, crop yields of irrigated and dryland agrivoltaic systems, water saving opportunities, soil hydrology impacts of solar projects, and soil quality.

Analytical research has focused on modeling ecosystem services of different vegetation and groundcover types, assessing the potential impacts of pollinator habitat at solar facilities on agricultural lands, characterizing the potential of agrivoltaic systems in off-grid areas, assessing operations and maintenance (O&M) costs of different groundcover types, and surveying existing groundcover types at solar facilities (Choi et al. 2021; 2020; Ravi et al. 2016; Walston et al. 2018; 2021). In addition, the InSPIRE project has created a data portal that houses relevant literature, an agrivoltaics primer, a simple financial calculator to assess agrivoltaic trade-offs, and a map of agrivoltaic sites (National Renewable Energy Laboratory 2022).

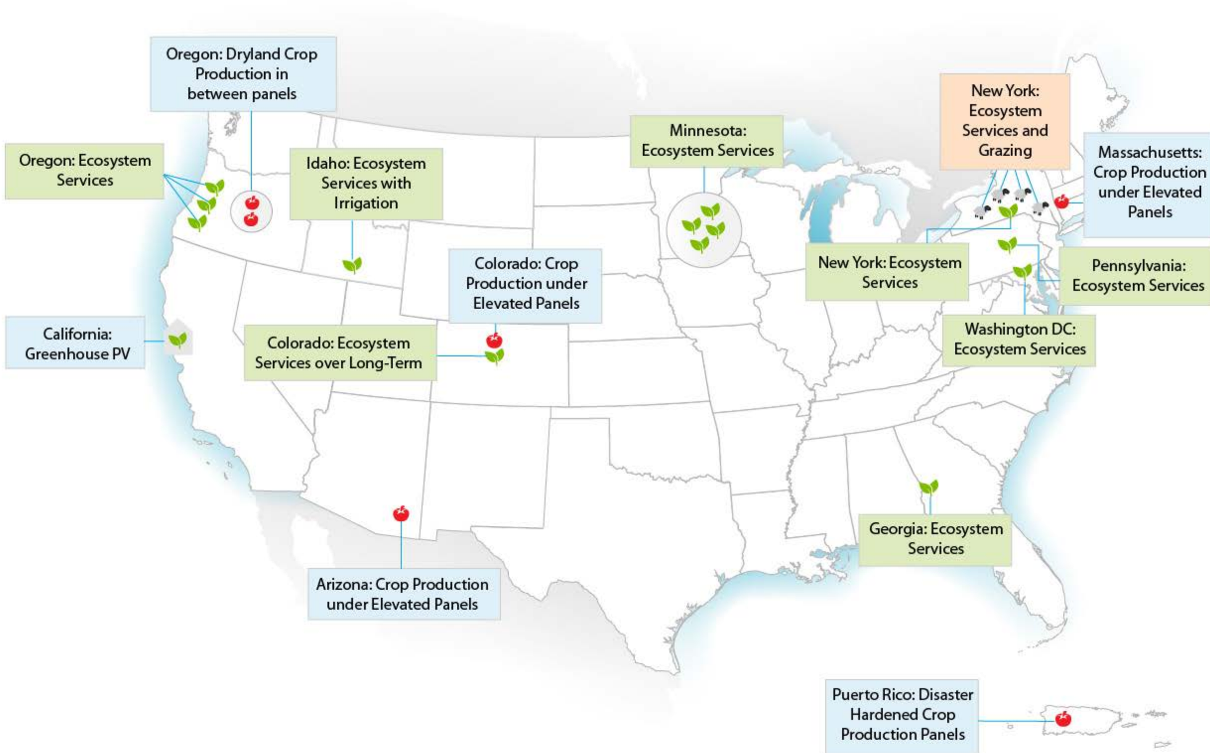


Figure 2. InSPIRE research overview.

3 The 5 Cs: Lessons Learned From the InSPIRE Research Study

Coordinated InSPIRE research efforts across project types, configurations, and regions have led to important insights relevant to successful agrivoltaic installations and agrivoltaic research activities. These lessons can not only inform future research activities, but also improve the likelihood of success of future agrivoltaic projects and partnerships. The lessons discussed here are focused less on specific case study outcomes (i.e., the percent change in crop yield in an agrivoltaics configuration) and more on the elements that enable agrivoltaics projects to be installed and operated and the factors that facilitate research at those sites. Even when agrivoltaic facilities are constructed, integrating robust research and long-term agricultural activities on those sites adds additional elements of complexity. We find that there are some insights that are applicable across all types of agrivoltaic projects, whereas ecosystem service projects and crop production agrivoltaic projects often have other unique considerations.

Lessons learned are categorized into five primary themes, termed "The 5 Cs" (Figure 3):

- **Climate**, Soil, and Environmental Conditions (C1): *The ambient conditions and factors of the specific location that are beyond the control of the solar owners, solar operators, agrivoltaic practitioners, and researchers.*

- **Configurations**, Solar Technologies and Designs (C2): *The choice of solar technology, the site layout, and other infrastructure that can affect light availability and solar generation.*

- **Crop Selection and Cultivation** Methods, Seed and Vegetation Designs, and Management Approaches (C3): *The methods, vegetation, and agricultural approaches used for agrivoltaic activities and research.*

- **Compatibility** and Flexibility (C4): *The compatibility of the solar technology design and configuration with the competing needs of the solar owners, solar operators, agricultural practitioners, and researchers.*

- **Collaboration** and Partnerships (C5): *Understandings and agreements made across stakeholders and sectors to support agrivoltaic installations and research, including community engagement, permitting, and legal agreements.*

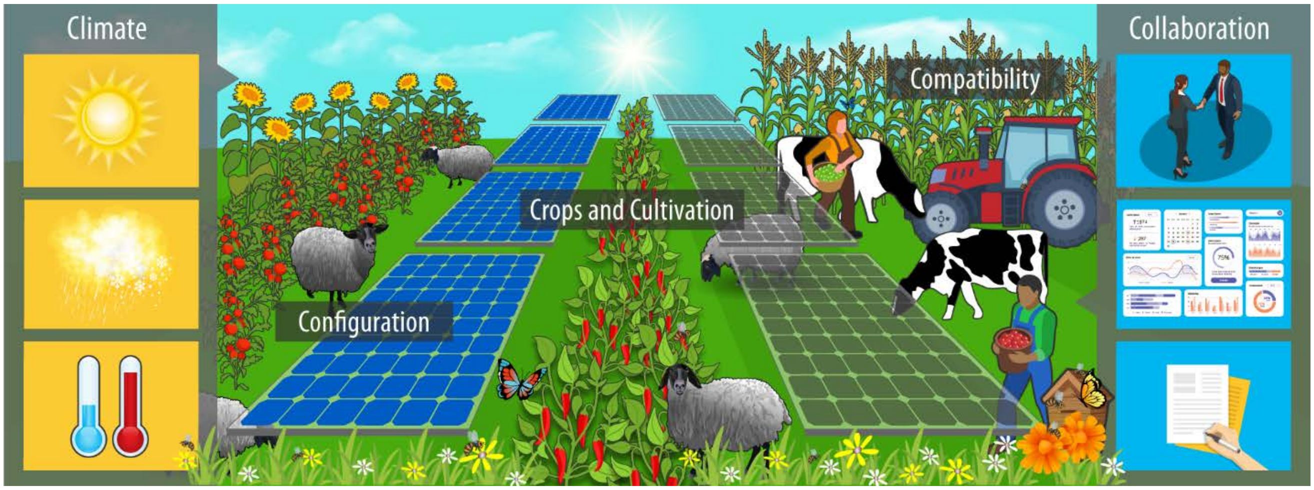


Figure 3. Determinants of agrivoltaic project success: the 5 Cs.

Most agrivoltaics literature is focused on the interplay between climate, soil, and ambient conditions (C1); configurations and technologies (C2); and crop and seed mix selection or cultivation approaches (C3). However, in nearly all cases, the compatibility of the infrastructure with agricultural activities (C4) and effective collaborations and partnerships among stakeholders from different sectors (agriculture, energy, academia, government, etc.) (C5) will drive the long-term success of installations and research efforts.

Interest in agrivoltaics projects and deployment has been rapidly increasing, yet relatively few solar projects in the United States are designed explicitly to be compatible with potential agricultural activities underneath or around the arrays. Many projects change developers or operators throughout the solar development and permitting process, meaning that decisions can be made by entities that are not going to be operating the site over the long term. Design decisions made early in the project development phase may impact the ability to successfully incorporate agrivoltaics activities (e.g., trailing edge panel height could limit the vegetation options in a pollinator-friendly design or a crop production design). Many factors—both within and outside of the control of the project developer—can contribute to final design decisions that affect the viability of agrivoltaics activities. If agrivoltaics projects cannot be built and operated successfully over the long term, then the validity of the research on these systems will be jeopardized and/or made less relevant.

An underlying theme affecting the success of agrivoltaic activities in the United States is project economics. Project economics must be viable for both the solar operations and the agricultural operations on-site. Projects are unlikely to proceed unless there is a clear economic value for both solar and agricultural partners. In some cases, modifications to the PV system design to accommodate agricultural activities can negatively impact solar infrastructure economics but positively affect agricultural economics, and vice versa. At the same time, these modifications to the PV system design could also result in an improved likelihood of successfully securing local permit approvals and expanding siting options for solar developers. Federal and state incentives, when available, can be used to offset increased capital costs for solar infrastructure as well as augment agricultural income.

Each of the 5 Cs is described in greater detail below.

3.1 Climate, Soil, and Environmental Conditions (C1)

The ambient conditions and surrounding land uses are beyond the control of the solar owners, solar operators, agrivoltaic practitioners, and researchers, but they can have a strong influence on an agrivoltaic project's success. Agrivoltaic systems should be designed to grow vegetation that is appropriate and feasible based on the available solar resource along with the ambient climate, soil, and other conditions. There is substantial diversity in local climates, soils, and ecoregions across the United States (US Environmental Protection Agency 2013), meaning that optimum conditions will be site-specific (Figure 4).

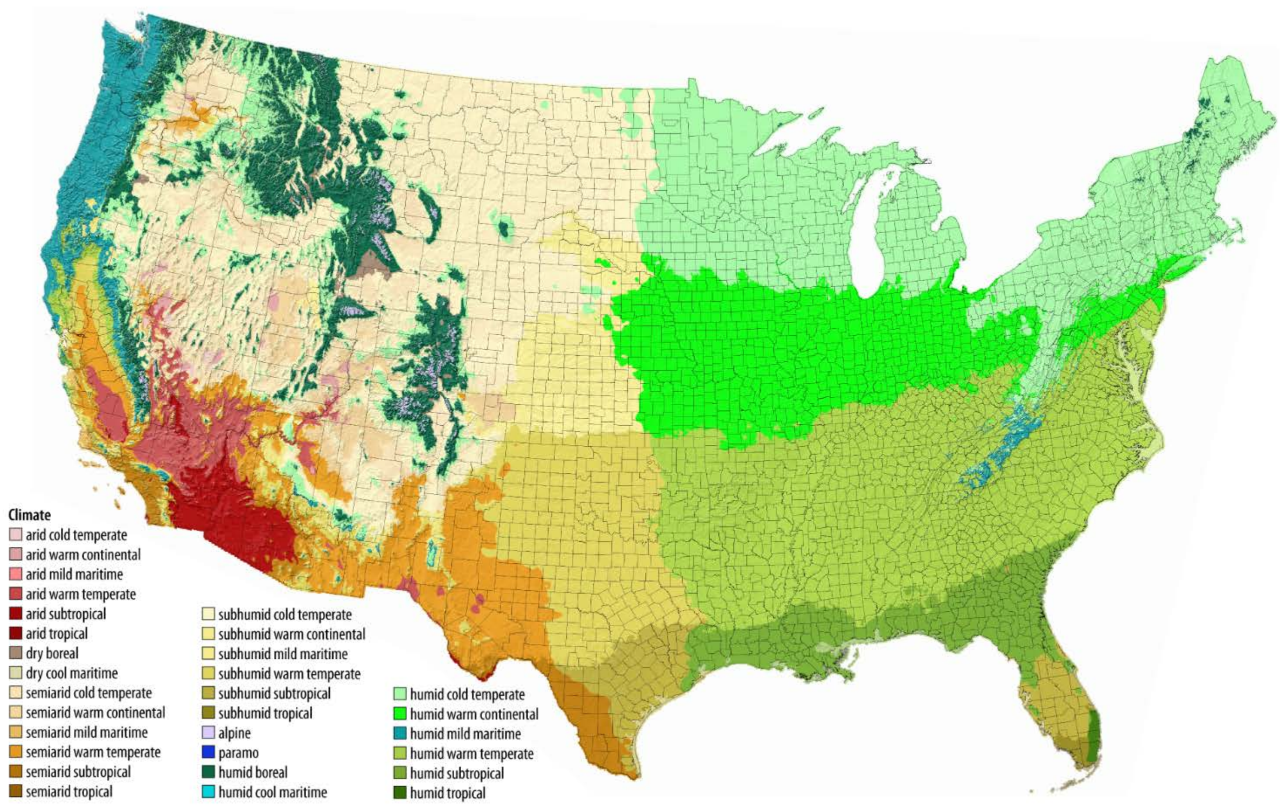


Figure 4. Climate zones of the lower 48 United States.

From (Kartesz 2015).

A summary of C1 technology configuration factors is shown in Table 2.

Table 2. C1 Climate, Soil, and Environmental Conditions

C1 Topic	Description	Code	Agrivoltaic Type
Ambient Climate	The ambient climate, including temperature, solar resource, wind, and seasonality, will be a primary driver of vegetation suitability.	C1	All
Soil Quality	Soil quality will affect the success of vegetation growth and hydrology on-site as well as affecting project risks and costs associated with stabilizing soils. Site grading and construction methods can affect soil compaction and topsoil quality.	C1	All
Prior and Surrounding Land Uses	Prior site uses and nearby land uses can affect vegetation on-site through drift of seeds, chemicals, wildlife habitat, insect populations, erosion, and soil quality.	C1	All
Water Access	Water is required for agrivoltaic activities, to support both vegetation and animals; if sufficient water is not available through precipitation, procuring water access and supply will be essential.	C1	All
Pests and Disease	Solar infrastructure can create conditions that lead to increases or decreases in disease or pest presence, which in turn can affect vegetation growth and animal health.	C1	Crop Production, Grazing
Additional Research Considerations			
Representativeness and Novelty	The degree to which the site's design, vegetation management approach, and local characteristics are representative of future applications, or are novel explorations of agrivoltaic topics, can determine the impact and relevance of the research.	C1	All
Nearby Land-Use Change	Changes in nearby land uses, such as crop rotation between pollinator-dependent and non-pollinator-dependent crops on nearby farms, or land disturbances, can affect vegetation and insect populations.	C1	All

3.1.1 C1 Factors Affecting Agrivoltaic Project Success

Ambient Climate

Much like traditional agricultural and utility-scale solar development, the solar insolation resource will be a primary driver of agrivoltaics success, affecting agricultural productivity as well as electricity generation. Agrivoltaic projects inherently lead to increased shade and altered sunlight patterns on a given parcel of land, both of which can limit vegetation growth in any area if shading exceeds plant needs, but which can also enable vegetation growth in areas where available sunlight is not a limiting factor or for crops (e.g., shade-grown coffee operations) that produce a higher quantity and quality of crops with shade canopies (Aroca-Delgado et al. 2018). Of particular interest is photosynthetically active radiation (PAR), which is the range of wavelengths most suitable for crops (Dinesh and Pearce 2016; Zainol Abidin, Mahyuddin, and Mohd Zainuri 2021). Beyond the total solar insolation resource, the diurnal patterns and seasonality of the solar insolation resource can affect vegetation growth potential (Figure 5). Alongside available solar insolation resources, other microclimate factors, such as temperature, relative humidity, and wind, can have a prominent role in determining suitable vegetation types and technology configurations for agrivoltaic projects. For example, agrivoltaic projects could enable agriculture in areas where average temperatures are currently too hot for common agricultural approaches. Conversely, a primary outcome of agrivoltaics is a reduction in available light and a decrease in daytime temperatures; if sunlight and temperature conditions are too low in open-air environments to support successful traditional agriculture activities, they will similarly not support vegetation establishment or growth in agrivoltaic contexts. Wind loading can also play a limiting role in determining suitable technology configurations, especially in regions with extreme wind conditions.

Figure 5. InSPIRE researchers measuring photosynthesis in different areas under a solar array at a research site in Colorado.

Soil Quality and Compaction

For any type of agrivoltaics installation, the starting quality of the soil is an important determinant of the success of the agricultural activity. Soil quality can be affected by natural conditions, the prior land uses of the site, the percentage of the site that was disturbed by preconstruction grading activities, and any construction impacts that led to compaction or degradation of topsoil. Even on previously tilled agricultural land, solar development can lead to soil compaction severe enough to affect soil quality and health (e.g., infiltration rates, micronutrients, bulk density, texture, conductivity, etc.) and vegetation growth. Decompaction post-construction can ameliorate impacts from grading and construction activities. Moreover, developers can use software to model preconstruction grading needs and choose the appropriate torque tube height and racking systems to fit with the topology of a given parcel to minimize grading, compaction, and erosion risks. Soil types and conditions can also affect the depth of steel, spacing of poles, and other design considerations to account for wind loading.

InSPIRE research showed that soil quality impacts were still present on an ecosystem service-providing solar site in Colorado nearly a decade after construction (Choi et al. 2020). Compacted soils, as well as soils depleted of essential nutrients or subject to repeated herbicide and pesticide use, are likely to have less successful vegetation establishment. Utilizing low-impact site preparation and construction techniques, as well as decompacting soils after construction, can help minimize the impacts of solar installation construction on soil quality.

Even within a relatively confined geographic area, there can be substantial differences across different sites and within sites related to soil type, soil quality, and land disturbance. Soil type (e.g., clay vs. sandy) can affect not only the type of vegetation that would be suitable, but also the growing techniques and water requirements needed to establish and maintain that vegetation. Certain areas may be prone to floods, and excess water or erosion could transport seeds to another location within the array. This can also affect the rate at which certain species grow. Ongoing efforts are assessing the soil and hydrologic impacts of solar development at the landscape level (e.g., the DOE-funded Photovoltaic Stormwater Management Research and Testing (PV-SMaRT) project (National Renewable Energy Laboratory n.d.)).

Assessing soil quality and characteristics prior to implementing agricultural activities can help ensure more effective agrivoltaic projects (Figure 6). In addition, complementary soil tests after solar project lifetimes can lead to insights about the long-term impacts of the agrivoltaic activities on soil health, which can help inform future decisions for that land parcel, such as project decommissioning or continued agrivoltaic operations.

Figure 6. Soil sampling to understand soil characteristics of an InSPIRE agrivoltaic site.

Prior and Surrounding Land Uses

Prior land uses, as well as the land uses of the surrounding region, can affect soil, vegetation, and wildlife within the solar array. Prior land uses include intensive crop production, rangeland, forested land, industrial activities, or other uses that result in varying levels of soil health. These activities might also include the use of herbicides and/or pesticides, the residuals of which can affect the success of new vegetation, wildlife presence, and human health, and can be a factor in scheduling project activities. Land management activities might also include installing drainage tiles or other belowground infrastructure that can affect soil characteristics and hydrology.

Adjacent land uses can affect the ecosystem dynamics of solar projects. The nearby presence of farmland, open fields, forest, and urban environments can affect the presence of vegetation, insects, hydrology, and pollution. These sites can be locations where insect or other animal habitat already exists, or not, which can affect the possibility of animal migration. Surrounding sites can also introduce new species, chemicals, or organisms to the site through wind and/or erosion. Adjacent agricultural activities can also lead to increased soiling on panels from airborne dust and particulates generated during tilling, planting, or harvesting activities (Figure 7), or naturally, such as from pollen released by corn. Importantly, surrounding land uses can change throughout the duration of the project, affecting the availability of habitat for wildlife as well as changing the risks of other effects.

Changing surrounding land uses can also affect the purported benefits of an agrivoltaic project. If pollinator-dependent agriculture is no longer being practiced near a pollinator-friendly solar project, the expected local agricultural yield benefits of that project will be reduced. In general, InSPIRE research considers pollinator habitat benefits to agriculture to be within a one-kilometer radius around the solar site, but other ecosystem services related to erosion control or insect predation could have different distance thresholds and could be relevant across multiple adjacent land uses (Walston et al. 2018; 2021).

Figure 7. Agricultural activities on active farmland adjacent to InSPIRE ecosystem services sites in Minnesota.

Water Availability and Access

Water is required for all types of agrivoltaic systems. If natural precipitation is insufficient to establish or maintain the desired vegetation and habitat, then supplemental water supplies will be needed—particularly at establishment. However, acquiring legal access to water, as well as finding a suitable mechanism for utilizing and distributing water on-site, can be important determinants of an agrivoltaics project's feasibility. Accessing water rights in the western United States can be especially challenging and expensive. Irrigation systems will likely have to be tailored for vegetation and crop production support, and mechanisms for supporting animal water needs might also need to be constructed. If water is not readily available to support the desired vegetation, projects might have to build new infrastructure (e.g., retention ponds, new wells, panel runoff redistribution systems) or transport water on-site to be utilized in agricultural activities. In some locations, water might not be available with certainty or regularity at different times of year. For grazing operations in particular, identification and management of a clean, reliable water source for livestock is an important consideration to maintain animal health.

Agrivoltaic systems can also be used to improve water efficiency and create improved water access (Barron-Gafford et al. 2019; AL-agele et al. 2021; Marrou, Dufour, and Wery 2013; Parkinson and Hunt 2020). The shade created by agrivoltaic systems can reduce water demands for vegetation due to lower evapotranspiration rates, which could reduce some water-related challenges. This can also help facilitate dry farming, where no supplemental irrigation is available or needed. For example, InSPIRE researchers in Oregon are exploring how agrivoltaics configurations can be used to reduce drought stress and blossom end rot in dry farmed tomatoes, improving fruit quality and yield of marketable tomatoes. Precipitation runoff, or even water used to clean panels, can be collected from panels with an adequate collection, storage, and distribution system in place that is compatible with the solar infrastructure and farming operations. In addition, energy from the PV system could be used to power pumps and/or treatment systems, depending on grid connections.

Using Agrivoltaics To Improve Plant Health: At the InSPIRE dry farming test site in Oregon's Willamette Valley, InSPIRE researchers from Oregon State University's Dry Farming Project are examining multiple approaches to minimizing blossom end rot of dry farmed tomatoes. InSPIRE researchers have hypothesized that the partial shade and wind protection from solar panels could help minimize blossom end rot in tomatoes by reducing plant drought stress. In this case, InSPIRE researchers have adapted their research and associated experiments to address a critical barrier to dry farming in Oregon that is of high interest to local farmers.

Pest and Disease Pressure

Nearly all utility-scale solar development sites face interactions and pressures from nearby wildlife. Agrivoltaics projects have similar wildlife issues as traditional utility-scale solar projects, as well as additional issues that traditional agricultural operations face. Certain insects, rodents, and other wildlife can affect crop yields, agricultural outcomes, and research. Diseases in plants and soil can also affect yields and research. There are potential concerns that any utility-scale solar project with new vegetation habitat, increased shading, higher moisture levels, and lower temperatures could lead to increases in rodent and other wildlife populations, which could have negative impacts on site infrastructure (e.g., gopher tunnels and chewed wires) and vegetation. Similarly, more moisture in the environment could lead to higher rates of plant disease in some environments. This is generally more of a concern in humid areas, such as the southeast United States. This was initially a concern for the Carter Solar Farm InSPIRE research site in Georgia; however, it has not presented a major challenge. At the Jack's Solar Garden site in Colorado in 2021, morning dew runoff from the tracking panels led to an increased presence of fungus on cucurbits in beds located directly under the panel edge. This issue could be remedied by placing the bed further away from the panel drip line, growing other crops in that bed, or strategically managing and directing morning dew. InSPIRE researchers at Cornell University are evaluating how varied agrivoltaic management systems with sheep grazing and ecosystem service production can affect pest populations.

Cornell University Solar Grazing Project: The Cornell Solar Grazing Project is a collaborative research effort focused on five solar arrays near the Cornell campus in Ithaca, New York. The project incorporates research on rotational sheep grazing (**1**) to assess their potential both as livestock and to limit plant height while generating new growth. Researchers across several disciplines collaborate to simultaneously measure the impact of the grazing regime on plant diversity, carbon sequestration, and beneficial insects, including pollinators (primarily bees) and predators (primarily ladybugs) that regulate insect pest populations. In 2020, over 160 species of plants were recorded across 600 sets of sweep net samples (**2**). This diverse complex of plant species supported a diverse group of pollinators with 19 bee species and 7 ladybug species, including some rare natives such as the three-banded ladybug (**3**). Adult ladybugs are attracted to some types of flowers, but eggs (**4**) and larvae (**5**) were also observed, indicating rich resources of prey such as aphids (**6**) as well as nectar. While ladybugs were a specific focus, several other groups that can suppress insect pests were observed, including a large and diverse group of spiders (**7**) and small wasps that parasitize aphids (**8**). Another important observation was the level of potential pest insects, especially the tarnished plant bug (**9**). Although data is still being analyzed, early results demonstrate that while there is some risk of fostering pest populations, there is also an opportunity to enhance ecological services and to conserve rare species.

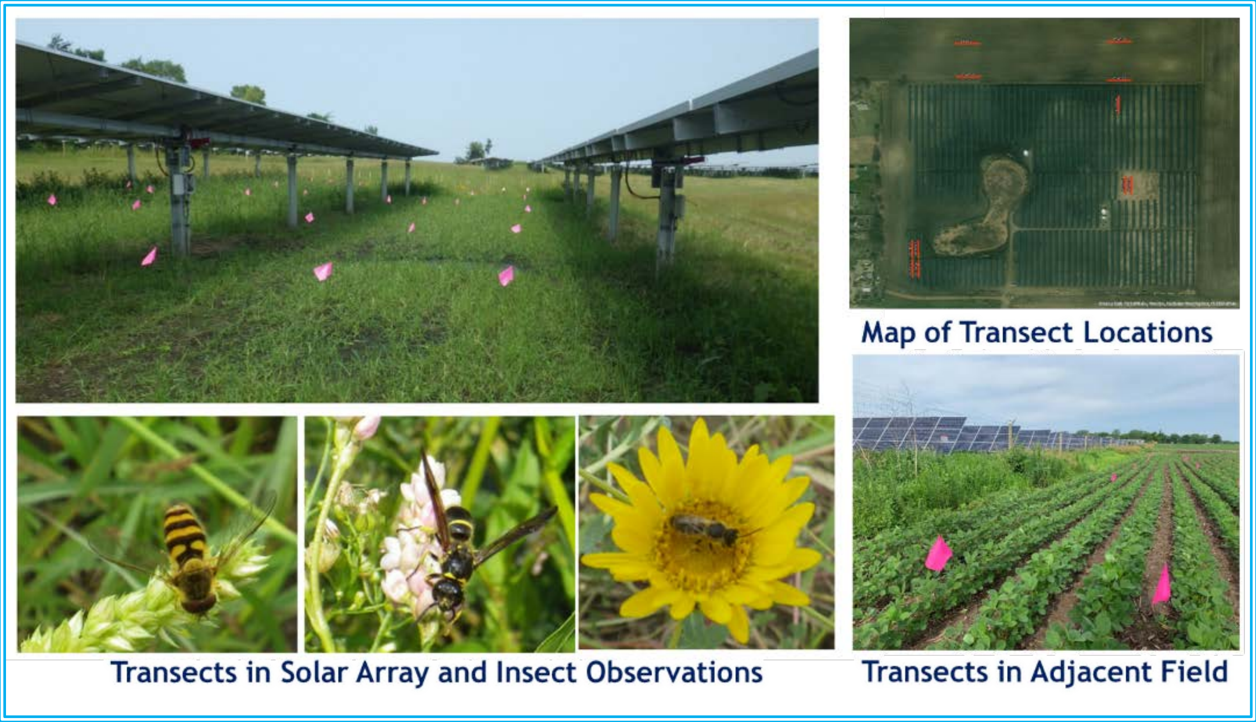
3.1.2 Additional C1 Factors Affecting Agrivoltaic Research

Representativeness and Research Novelty and Value

Research design and selection of sites should include a consideration of whether the agrivoltaics site has climate and ambient conditions that are relevant to future agrivoltaics installations. Other considerations can include whether the site could provide novel or foundational information that can benefit agrivoltaics knowledge in general, and whether the research is significantly different from other ongoing research in the area. Maintaining awareness of recent scientific literature, developing clear agreements with partners on groundcover management approaches, and understanding agricultural stakeholder expertise and perspectives can all help ensure that the research has the potential to be relevant and impactful. Because agrivoltaics research is at an early stage of maturity, there is generally not a saturation of research or locations, and most agrivoltaic sites are still providing novel data. Coordination and collaboration with nearby sites can play a key role in helping improve the overall quality of research. In addition, research trials should focus on configurations that are indicative of the designs that would be implemented at scale for future farming activities to ensure broad applicability of the research results. Moreover, appropriate land management practices and diverse groundcover at the site are crucial to ensuring the relevance of the research. The InSPIRE team selected three sites in Minnesota that are part of Enel Green Power's Aurora project, working with the solar developer, the vegetation management company, agencies in the state of Minnesota, and biologists to identify sites that spanned different ecotypes and soils. The team also worked with the state to evaluate recommended seed mixes for pollinator habitat. In some markets, like Puerto Rico, proof of concept pilots could play a crucial role in increasing the readiness of the renewable energy industry to venture into agrivoltaics, as well as playing a key role in the standardization of designs and components. In turn, this could contribute to the cost-effectiveness and market penetration of agrivoltaic solutions.

Nearby Land-Use Changes and Crop Rotation Outside of the Agrivoltaics Array

For research projects addressing pollination benefits to nearby agriculture, the crop rotation schedules of farms outside of the agrivoltaic array may limit the research design or potential research outcomes. For example, corn and soybeans are generally rotated on an annual or biannual basis, and corn is not a relevant crop for pollinator studies because it annually releases pollen that is carried by the wind instead of being moved via insect pollination. Therefore, for short-term studies (1- to 3-year duration), it will be difficult to collect adequate data on soybean pollination benefits provided by pollinator habitat. However, for longer-term studies (4- to 6-year duration), if farmer partners are identified early in the study and planting plans are known, the study can be designed to accommodate the crop rotation schedule.



Coordinating On-Site Research With Adjacent Land-Use Changes: At the Enel Green Power Aurora Solar Project sites, InSPIRE researchers from Argonne National Laboratory are coordinating their beneficial insect field surveys with local landowners and farmers, who rotate crops between corn and soybeans. The research design and location of surveys can change each year depending on landowner agricultural activities. The InSPIRE team proactively reaches out to farmers ahead of the growing season to facilitate successful field work.

3.2 Configurations, Solar Technologies, and Designs (C2)

The choice of solar technology, the site layout, and other infrastructure can affect light availability, microclimate, soil conditions, and solar generation economics. Each component of the configuration must be evaluated in the context of the entire system design. For example, increased panel heights will have different impacts on groundcover vegetation depending on the inter-row spacing, inter-panel spacing, and the level of transparency of the panels (Figure 8).

Importantly, because configuration designs are not generally able to change,[6] decisions made during the design phase will be fixed for the duration of the project, which can be 20 to 30 years.

[6] Retrofitting a project during the middle of its project lifetime could offer an opportunity to change some design configuration details, but this is likely to be rare.

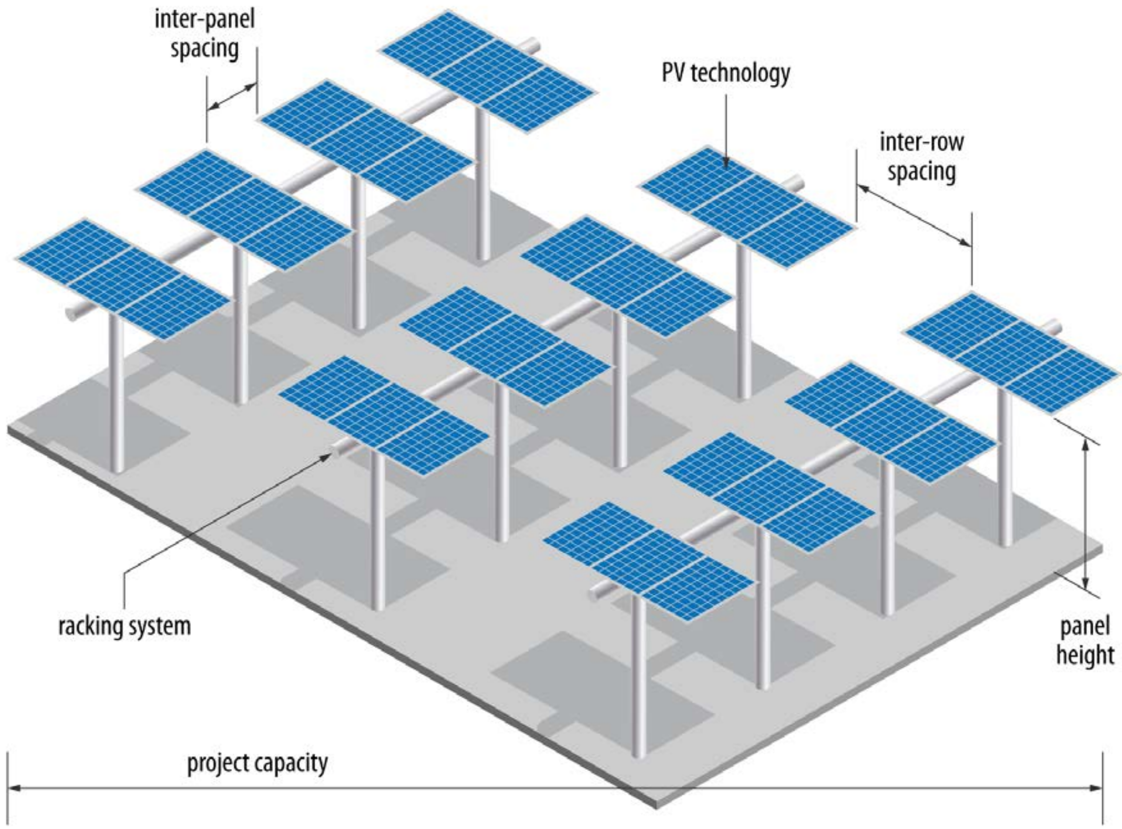


Figure 8. C2 configuration and technology characteristics.

A summary of C2 technology configuration factors is shown in Table 3.

Table 3. C2 Solar Technology and Configuration Considerations

Topic	Description	Code	Agrivoltaic Type
Project Capacity	The capacity (MWdc) of the project can affect its financing opportunities and market, which can limit capital-intensive modifications to system design. The size can also affect the feasibility of certain agricultural activities, land-use change impacts, and permitting.	C2	All
Panel Height	Panel heights, including bottom and top edges, can affect what vegetation and crops can grow, compatibility with workers, animal presence, and project economics.	C2	All
Racking System	Racking systems can affect land available for agricultural activities; shading levels; compatibility with equipment, workers, and animals; and project economics.	C2	All
Panel Spacing	Panel spacing can affect available sunlight and microclimate conditions, as well as worker and equipment access.	C2	All

Topic	Description	Code	Agrivoltaic Type
Row Spacing	Row spacing can affect available sunlight and microclimate conditions, as well as worker and equipment access.	C2	All
PV Technology	The choice of PV technology (e.g., semi-transparent modules, bifacial modules, opaque modules) can affect available sunlight and microclimates that in turn affect vegetation growth and project economics.	C2	All
Additional Research Considerations			
Project Land Area	The land area of the overall project can affect the type of research that can be performed, especially at the landscape scale. Research projects with minimal land area might not provide scalable outcomes.	C2	All

3.2.1 C2 Factors Affecting Agrivoltaic Project Success

Project Capacity

Project capacity (MWdc) can affect the feasibility of agrivoltaics activities on a solar site, in part due to how project economics might affect the feasibility of other design and configuration changes. Smaller projects (e.g., <1 MW) that are designed for use in an off-grid setting, for participation in net-metering programs, or as part of other market mechanisms where incentives are available, might have greater flexibility for making design modifications to allow for a greater diversity of agrivoltaics activities. Larger, utility-scale projects are often subject to a highly competitive bidding process, but can also face a multi-year queue and transmission costs that approach 50%–100% of the project cost (Caspary et al. 2021). In these projects, small adjustments to configurations, such as increased panel heights and associated steel costs, can lead to cost increases that make the project less economically competitive than others. Agrivoltaic activities may also not be cost-effective for smaller projects in renewable energy markets and agricultural sectors where the concept of agrivoltaic systems has not been proven, where the systems need to be custom-made, or where significant barriers exist for ground-based elevated designs (e.g., topography, extreme wind loads and weather events, critical need for batteries or energy storage).

The size of the project can also have an important impact on the types of agricultural activities that can be performed on-site, as well as their economic viability. For crop production systems, project size can affect the types and methods of agricultural production. Crop production systems can involve hand-harvesting or equipment and machinery. Larger sites (e.g., >1 MW or ~5 acres) often require some equipment and machinery for farming activities, which means that the PV installation's design and configuration need to accommodate equipment specifications. Projects with only a few panels will have lower shading and microclimate impacts than larger installations, and might not be large enough to support commercial agricultural operations.

For ecosystem services sites incorporating native vegetation and beneficial insect habitat, projects over 100 MW could potentially see different levels of ecosystem services within the interior of the site compared to the edges of the project. For example, pollinator habitat in the interior areas of large sites may not benefit pollination in nearby agricultural fields, because the distance from the site interior might extend beyond the regular foraging range of some beneficial insects (Walston et al. 2018). Creation of native habitat and a management regime to facilitate native insects is likely to provide other ecosystem services, such as water retention, erosion control, carbon sequestration, and increased biodiversity. Conversely, projects that are less than 20 kW, taken individually, might not create adequate habitat to have a substantial impact on insect populations or ecosystem services.

For grazed solar projects, the size of the project is one factor that informs the appropriate number of livestock and duration of their stay at the project. Larger solar projects were found to have a high labor requirement by the grazing manager due to the need for temporary livestock fencing. Smaller sites can save on labor for installing fencing, but due to factors such as travel distance, they may require more frequent livestock hauling, and therefore might not be a net savings compared to larger sites.

Panel Height

Panel heights can affect the success of different types of vegetation underneath the solar installation, along with the feasibility of people, animals, and equipment having access to and managing that vegetation. In general, elevated solar infrastructure can facilitate a greater diversity of agricultural activity underneath and around the arrays, but this comes with increased solar installation costs. Project designs that necessitate crews to primarily use ladders and lifts in the construction process are likely to see higher labor costs than projects with torque tube and/or rack heights reachable within an average person's height. Ideal infrastructure heights depend on the specific vegetation underneath the arrays and the proposed equipment or management approaches. Depending on the local climate and soil conditions, elevated panels may also require different and more robust design considerations to ensure safe operation. For example, in humid subtropical regions, elevated infrastructure might need to be hardened against increased wind loads, whereas in cooler regions, elevated infrastructure might need to be reinforced against large snow loads. All of these factors can lead to increased design, materials, and installation costs, as well as increased risks.

For native vegetation and beneficial insect agrivoltaic sites, there are currently a limited number of commercially available seed mixes through existing supply chains that can be utilized and provide the expected ecosystem services for projects that have less than 3 feet (1 meter) of clearance height. Lower panel heights, if not designed or implemented with appropriate seed mixes, can lead to lower species diversity and thus fewer blooming or otherwise beneficial species at different times of year. This can also affect insect populations, insect pollination and predation activities, soil erosion control, and other ecosystem services. Lower panel heights can also lead to an increased frequency of mowing events to manage vegetation and prevent panel shading; fast-growing weedy species and woody vegetation are more likely to impact panels with lower height configurations. There are no established ideal panel height recommendations, as this can change depending on region, vegetation selection, soil types, and cost drivers, but an overarching rule is to select vegetation that has a high likelihood of successful establishment, establishes within 2 to 3 years, and does not grow tall enough to shade the panels, while still meeting site vegetation objectives (e.g., high-value pollinator, native seed selection, ecosystem services, etc.).

For crop production systems, panel heights are often the primary factor in determining the types of crops that can be grown and the equipment that can be used. Panel heights can also influence whether crops will be grown only in between rows of panels or if they can be grown underneath panels. From InSPIRE research sites, torque tube heights of 6 feet (1.8 meters) appear to be the minimum viable height for vegetable crop production under panels, given the shading regime and farmer interactions, though farmers prefer torque tube heights of 8 feet (2.4 meters) or higher. Higher panel heights also enable a more uniform shading distribution, which may be especially important in cases where uniformity in crop sizes and timing to harvest are required (such as in larger-scale production agriculture). Greater heights also allow people and smaller-scale equipment to go underneath panels safely, while also reducing the potential for accidental damage to infrastructure or injury to farmers. At heights below 6 feet (1.8 meters), crop production will likely be confined to the areas between panel rows, unless there are low-height, shade-loving crops that can be safely and effectively harvested. Lower heights can limit total land availability for farming activities and potentially increase management time for the nonproductive land underneath the panels.

For grazing systems, most standard utility-scale solar panel heights can accommodate sheep grazing, but elevated panel heights are generally needed for cattle grazing. For all animals, wire management systems should be properly encased to avoid interactions with the animals.

Panel Height Considerations and Side-by-Side Comparisons: At Jack's Solar Garden in Colorado, InSPIRE researchers are studying the impacts of two different panel heights (6-ft and 8-ft torque tube height) on vegetation growth and farmer compatibility. Researchers are examining crop production, soil moisture, microclimate conditions, pollinator habitat growth, and pasture grasses under both panel heights. The available light is more evenly distributed under the 8-ft panels than the 6-ft panels, which can lead to more consistent growing conditions in each row. The team is also gathering insights from the commercial farmers from Sprout City Farms on-site, who are providing feedback on the compatibility of farming activities under both panel heights.

Racking System

The type of racking system can play a large role in determining what type of agricultural activity is feasible and how successful it will be. Racking systems affect how much land is available for vegetation, crops, and animal activities. Racking system designs that are able to follow the contour of the land and/or that minimize the number and ground coverage of piles and other support structures generally allow for more agricultural activities. Local terrain (e.g., flat, sloped, uneven) can limit racking options for solar developers, which in turn can affect access, groundcover ratio, and shading for agricultural activities. Racking systems that include aboveground drive lines or cables can limit access of people and equipment. Racking system design also includes choosing between fixed-tilt and tracking arrays. Fixed-tilt arrays can be less capital-intensive, with lower O&M costs and a higher power density (more kW capacity per area of land), but tracking systems can provide greater generation per unit of land with the trade-off of O&M expenses to maintain the tracking systems. In general, tracking arrays provide higher kWh per MW than fixed-tilt arrays. The choice of fixed-tilt vs. tracking systems will also affect the shading regime under and around the panels; the distance between rows of panels (tracking systems generally have larger spaces between rows); and person, animal, and equipment interaction with the infrastructure. Tracking systems generally allow for expanded options for plant communities under the array. Tracking systems can also allow for customization of tracking algorithms, which can be used to support co-optimized tracking angles to support plant growth or to accommodate agricultural equipment during times of land preparation, planting, maintenance, or harvesting. In the United States, most agrivoltaic systems use traditional fixed-tilt or tracking systems; however, there are also unique designs that have been deployed in other countries. Innovative racking systems include vertical bifacial systems, which can allow for greater equipment access (Tahir and Butt 2022; Riaz et al. 2021; Campana et al. 2021), as well as other designs that enable wine grape production (Rollet 2020). Racking systems can limit farmer and equipment access during certain times of day due to panel positions. Relatedly, racking systems can also come in contact with people, animals, and machinery; the rough metal edges in some racking systems can cause injury and/or damage more often than racking systems with smoother metal edges.

Racking systems also affect localized soil hydrology due to precipitation runoff. Fixed-tilt systems lead to consistent runoff patterns below the trailing edge of the panel. Tracking systems lead to variable runoff patterns, depending on the panels' position during precipitation events. Both of these systems can affect vegetation growth under the arrays; the excess moisture can lead to enhanced vegetation growth in some cases and plant disease in others.

Inter-Panel Spacing

Traditional utility-scale solar installations have minimal spacing between panels. Increasing the space between panels facilitates greater penetration of sunlight to the agricultural area, but leads to a lower energy density (MW of power per unit of land area). The additional sunlight can positively or negatively affect vegetation growth, depending on local conditions and vegetation types. The additional sunlight that reaches the ground can also reduce the other impacts of partial shading of the arrays, including moderation of the microclimate conditions in the array, protection from weather, and higher levels of soil moisture. Inter-panel spacings could also have other benefits for crop operations, as the spaces between panels can enable greater access for farmers to go in between rows and beds, which could lead to more efficient farming practices. In places where land availability and land costs are not severe, the lower energy density associated with increased panel spacing can be an acceptable trade-off. There can be some concerns with inter-panel spacing for tracking systems due to the connection points of panels and racking infrastructure; racking system designs must be compatible with the distance of panel spacings.

Inter-Panel Spacing Experiments: At the University of Massachusetts South Deerfield agrivoltaics research site, InSPIRE researchers are studying the impacts of different inter-panel spacings on crop production for elevated, fixed-tilt panels. The panel spacings are 2 ft, 3 ft, 4 ft, and 5 ft, and crops are also analyzed based on the 23 different north-south positions they can have in relation to being directly underneath the panel, under the trailing (bottom) edge, or in the spaces behind the panels. Results have shown some initial differences and preferences among crop types in this climate for larger spacings (e.g., peppers) and smaller spacings (e.g., chard).

Inter-Row Spacing

Increasing the distance between rows of panels can enable the use of larger farm equipment, more beds and rows of crops in a given land area, and greater room for movement of farm workers. Like inter-panel spacing, greater distances between rows can reduce the groundcover ratio. This can affect project economics in areas with high land costs or limited land availability, but can also increase the likelihood of farmer compatibility and agreement. Increasing the spacing between rows provides more area for vegetation to grow and more equipment access, and can also reduce the other impacts of the solar infrastructure's partial shading, including microclimate conditions, protection from weather, and soil moisture. An under-construction 1.2-MWdc InSPIRE agrivoltaic research site in partnership with the Denver Botanic Gardens

Chatfield Farms will be incorporating three different inter-row spacing distances to evaluate the impacts on crop performance and farmer compatibility.

PV Technology

PV modules can be composed of different materials that have varying densities and opacities at the array level. The most commonly deployed PV technologies for utility-scale solar projects are monofacial silicon PV modules, although thin-film cadmium telluride (CdTe) and bifacial PV panels are also prevalent. Different materials can lead to variations in shading and available sunlight for crops and other vegetation (Figure 9). For example, (semi-)transparent PV materials allow additional light to pass through to the vegetation, including light with wavelengths tailored to support crop growth. Cell spacing within opaque panels can also alleviate shading while avoiding some challenges of spacing panels; this can also lead to more homogeneous light diffusion. Bifacial panels can benefit from the reflectance of the groundcover, leading to open questions regarding which types of groundcover have the highest albedo and could lead to the most additional electricity generation. Early and long-running InSPIRE research sites have used monofacial technologies, but in 2022, the InSPIRE project started evaluating bifacial panels.

Figure 9. Agrivoltaics research site at Colorado State University's Agricultural Research, Development, and Educational Center (ARDEC) facility with monofacial, translucent, and bifacial panels.

3.2.2 Additional C2 Factors Affecting Agrivoltaic Research

Project Land Area

A solar project's land footprint can affect the types of research that can be performed as well as the potential implications of the research. Project sites greater than an acre can better facilitate landscape-level research projects that evaluate the impacts of land transformation. Larger projects can also facilitate greater numbers of treatment variations and/or support simultaneous research projects, which can provide useful research outcomes and minimize the challenges associated with comparing results across project sites. Larger sites are also suitable for utilizing a smaller portion of the site for research, which could lead to fewer disruptions to the management of the rest of the site. Larger sites help minimize edge effects near the boundary of the solar infrastructure, which can differ from areas that are in the interior of the solar array. However, larger sites also have some drawbacks. They can be more challenging to access and can be located in more remote areas. In addition, edge effects are often important to characterize, due to the fact that many insect foraging distances are less than the width of large solar projects. In some cases, especially with crop production, meaningful research activities require less than an acre of land. Ecosystem services and grazing studies generally require larger site sizes to achieve scientifically meaningful outcomes.

3.3 Crop Selection, Cultivation Methods, Seed Selection, and Management Approaches (C3)

The methods, vegetation, and agricultural approaches used in agrivoltaic activities and research can affect project success. Cultivation methods, research methods, and vegetation selection should follow best practices and be aligned with technology characteristics (C2) and climate and soil conditions (C1). Seed mixes and vegetation types have varying levels of success depending on site-specific conditions (Figure 10).

Atwater – Z1 | Chisago – Z1 | Eastwood – Z1

Figure 10. Identical seed mixes planted on three separate InSPIRE research sites in Minnesota.

A summary of C3 crop selection and cultivation factors is shown in Table 4.

Table 4. C3 Crop Selection and Cultivation Methods Determinants

Topic	Description	Code	Agrivoltaic Type
Vegetation Selection	Appropriate vegetation species and cultivars that can thrive under agrivoltaic conditions in that location and do not shade panels are crucial to success.	C3	All
Vegetation Establishment	Utilizing best practices for establishing vegetation will ensure that preferred vegetation will thrive over undesirable species and reduce reestablishment costs if seeding is not successful.	C3	Ecosystem Services
End Use, Markets, and Distribution	Having a defined end use or market for the sale and/or distribution of agricultural goods produced can affect farm economics and project viability.	C3	Crop Production, Grazing
Additional Research Considerations			
Research Plot Size	The size of the research plot in relation to the overall project size can influence the potential implications of the research outcomes. Plot sizes that are too small might overlook impacts that are taking place throughout the project site.	C3	All
Research Duration	Short-term (e.g., one year) studies can provide initial insights and certain types of data, but longer-term studies can provide more robust outcomes on vegetation performance that account for inherent variability.	C3	All
Complementary Modeling and Validation	Linking field research data collection to modeling validation efforts can lead to improved quality and robustness of research activities.	C3	All
Control Plot Design	Selecting appropriate control plot(s) for comparison can affect research takeaways and outcomes. Control plots could include vegetation-only and/or solar-only designs that are representative.	C3	All
Established Research Methods	Following established research protocols will improve the quality of the research and enable communitywide learning and sharing of results.	C3	All
Common Metrics	Utilizing metrics that are relevant and meaningful across sectors and partners (e.g., landowners, farmers, academia) will lead to improved and higher-impact research outcomes.	C3	All

3.3.1 C3 Factors Affecting Agrivoltaic Project Success

Vegetation Species and Cultivar Selection

For vegetation, grazing, and crop production systems, selecting appropriate vegetation species and cultivars is essential to ensuring a successful agrivoltaics project. Determining what appropriate species and cultivars are, and why, is the subject of ongoing InSPIRE and other research efforts, and is largely based on regional climate, water, and soil conditions. Often, the selection of vegetation must also fit into a broader context of externally driven preferences, such as landowner desires for only native species or local ecotypes. Species that thrive in the partial shade environment can sometimes be counterintuitive; for example, in an ecosystem service InSPIRE research site in Colorado, researchers were surprised when the "sun-loving" grass species dominated the "shade-loving" grass species in the research test plots (Beatty et al. 2017). In addition, different cultivars of the same species (e.g., potatoes) can respond very differently under the same conditions, as shown in InSPIRE research in western Oregon (Garrett, Nebert, and Homanics 2021). Most crop types have shown variations in performance depending on location and configuration (Figure 11). Some crop types (e.g., the nightshade family) have an impact on soil conditions, and planning for crop rotation over multiple years may be needed. Selecting a diversity of species and cultivars on a trial basis can be an effective mechanism to better understand which species will be successful at a specific site or region, with evaluation of crop vegetation success done either annually (for crops) or at approximately five-year intervals after initial seeding (for vegetation/ecosystem projects).

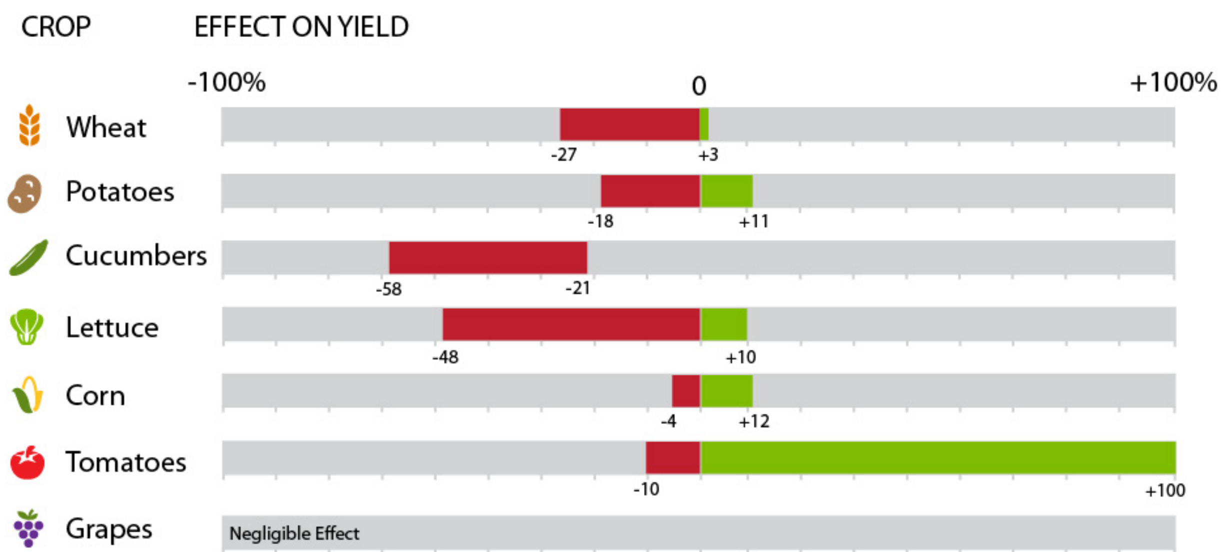


Figure 11. Summary of agrivoltaic crop performance across multiple sites and locations.

Data from (Amaducci et al., 2018; Barron-Gafford et al., 2019; Campana et al., 2018; Campana et al., 2020; Cho et al., 2020; Cossu et al., 2014; Dupraz et al., 2011; Leon and Ishihara, 2018; Marrou et al., 2013a; Marrou et al., 2013b; Prannay et al., 2017; Sukiyama and Nagashima, 2017; Trommsdorff et al., 2021; Valle et al., 2017)

Project managers should plan for the possible need for full or partial reseeding with different species. It is worth noting that optimal and well-adapted seed mixes and vegetation types for different regions, climate zones, soil conditions, and solar configurations is still a subject of research, and many insights tend to be site-specific or limited in geographic reach. In some cases, seed mixes and vegetation types that are commonly used without shade will be suitable in an agrivoltaics context, whereas in other cases, the seed mixes and vegetation types might need to change to ensure comparable performance.

Different states have differing local conditions, economies, land uses and types, ecosystems, agriculture, and policy environments. With regard to groundcover, there are differences in states' interpretations as to whether solar panels and the land beneath them are impervious or pervious surfaces, as well as what constitutes "establishment" with regard to finalizing stormwater permits. Impervious vs. pervious determinations can significantly affect project designs and vegetation selection plans to address stormwater management. Determination of vegetation "establishment" can affect the speed of closing necessary permits, a common condition before the project can be sold to a long-term asset owner.

More than a dozen states have adopted scorecards with broadly consistent measurement mechanisms that provide guidance as to what constitutes "beneficial to pollinators" for solar facilities in that state. The scorecards reflect some state-by-state differences, but they each include criteria such as diversity of species, number of blooming species, relative use of native and naturalized species, and planned use of seed treatments or broadcast pesticides. The first of these scorecards was published in 2016 by the Minnesota Board of Water and Soil Resources (BWSR) following input from energy, conservation, and agricultural stakeholders, with an explicit aim of providing guidance and avoiding misleading claims (Davis 2016).

In states where scorecards are published, state agencies and universities (e.g., Virginia Department of Conservation and Recreation, Illinois Department of Natural Resources, Michigan State University, Maryland Department of Natural Resources, University of Vermont, University of California-Davis, Purdue University) have collaborated to develop similar scorecard guidance for solar developers, energy buyers, and other stakeholders.

Several sites included in InSPIRE research now have mature vegetation as well as pollinator-friendly solar scorecards and documented pollinator responses. In Minnesota, Monarch Joint Venture's observational study of four InSPIRE sites (Lukens 2021) included copies of completed scorecards. Others are available from nonprofits and directly from BWSR (Davis 2021). In Virginia, an assessment of the first solar project of the state's "Pollinator Smart Solar" standard was recently published (Martin 2022), and summaries of observational research on projects with published scorecards have also been highlighted in the journal *Science* (Graham et al. 2021; Purnell et al. 2021).

There is ongoing discussion in states and in industry regarding the thresholds for verifying whether a site can be considered pollinator-friendly. Compounding this challenge related to selecting and establishing groundcover, there are also questions related to verification of continued vegetation over time, natural species successions, and percent cover evolution over time.

Vegetation Selection and Seed Mix Trials Across Soil Types and Ecoregions: At the Enel Green Power Aurora Solar Project sites in Minnesota, InSPIRE researchers are examining the establishment of eight different pollinator habitat mixes across three sites, each of which has different soil composition and hydrology characteristics. The team is also working with local vegetation management company Minnesota Native Landscapes (MNL) on different site preparation, seeding, and vegetation management approaches to understand which methods are the most cost-effective for encouraging successful establishment. Vegetation management approaches include the utilization of cover crops, mycorrhizal inoculation, and mowing frequency variations. The seed mixes were designed by the state of Minnesota, three local seed providers, and InSPIRE research biologists. The images above provide a representative example of progress in vegetation establishment at the Aurora Solar Project site in Chisago, Minnesota, from 2018 (top) to 2022 (bottom).

Seeding Approach and Vegetation Establishment

Different site preparation, seeding, and maintenance approaches can affect the success of vegetation establishment for ecosystem services, pasture, and crop production sites. Site preparation activities can include different levels of vegetation removal, herbicide application, and soil tilling, as well as soil testing and amendment. For crop production systems, planting approaches can be similar to open-air environments, where certain crops are direct-seeded and other crops involve transplanted seedlings. The altered shading regime could affect the germination rates of direct-seeded crops.

Seeding for ecosystem services and pasture grazing is generally completed using broadcast or drill-seeding approaches (Figure 12). Raking and other approaches can be used after seeding to encourage greater seed-to-soil contact. Certain cover crop species (e.g., annual rye, oats, winter wheat) can be planted at the same time as the seed mixes for early germination, serving as a nurse crop for newly germinated seeds to support vegetation growth and maintain soil stability. Supplemental irrigation can also be applied to support germination, especially in arid regions. Seeding usually occurs in the spring or fall seasons; in some cases, seeding in spring could require cold stratification prior to planting, a process in which seeds are kept at cold temperatures for extended periods of time to mimic winters. These approaches can differ in their success depending on the local climate, recent weather, and common practices, and are the subject of ongoing InSPIRE and other DOE research.

Figure 12. Drill-seeding (left) and broadcast seeding (right) of pasture grass mixtures at Jack's Solar Garden.

Just like in non-agrivoltaic projects, successful establishment of vegetation can take multiple growing seasons. Once vegetation is established, maintenance activities can include periodic mowing, timed to reduce weed pressure but also to support desirable vegetation. For pollinator habitat, thatch management is important to ensuring a diversity of species are able to thrive, as thatch can prevent multiple species from surviving. For native vegetation and pollinator habitat, successful maintenance activities might include a minimum of one to two mowing events in the first two years. Mowing frequency can be reduced over time. Also similar to non-agrivoltaic sites, targeted use of herbicides is also sometimes used to manage noxious weeds and woody vegetation, the removal of which can be required by law.

The level of experience of solar developers and operators as well as vegetation installation and management companies can affect the quality as well as the overall success of the vegetation effort. For pollinator habitat creation, there are benefits to working with contractors with solar or vegetation restoration experience versus landscaping contractors. Local knowledge of growing seasons, site conditions, and flora in the local ecosystem can benefit the establishment of vegetation on-site. The AgriSolar Clearinghouse Forum offers a platform for connecting service providers with sites and companies looking for experienced vegetation management partners (National Center for Appropriate Technology (NCAT) n.d.).

Vegetation Establishment and Plant Successions in Georgia: On a seven-acre InSPIRE research site where former president Jimmy Carter's family used to grow peanuts and soybeans, there now sits a solar project designed to attract pollinators and beneficial insects. The research included three different seed mixes planted in 2019, and thus far, only about 35% percent of the species planted have established well on the site. However, the species composition changes each year with the natural plant succession, and new species from the three planted mixes appear each year. This project is leading to important insights regarding establishment approaches for ecosystem service vegetation on solar sites in the southeast.

Agricultural Markets and Distribution

Agrivoltaic projects producing goods for sale or donation (e.g., crops, lamb, wool, honey) should have markets identified for off-takers of those goods. Equally important is identifying storage (e.g., refrigerated spaces) and distribution mechanisms prior to production. Farmers must also consider any processing needs, distance to markets, and other logistical challenges to make the activity economically viable. For solar grazing with sheep, an important consideration is the availability and proximity of butchers to process the meat and other processors for the wool. Agrivoltaic research sites also must consider whether the food will be eventually consumed or if it will be destroyed as part of the research activity (e.g., measuring dry weights of plants). There is potential to use agrivoltaics branding on crops to increase the desirability of products, which could result in the products commanding higher prices. For example, agrivoltaic honey production is marketed by highlighting the pollinator-friendly solar arrays (e.g., Clif Family, Bare Honey), where beekeeping operations are located on-site or adjacent to the solar facility (Figure 13). High-value specialty crops such as saffron have also shown promise for being economically viable (Ghalehgolabbehbahani, Parker, and Skinner 2022).

Figure 13. Honey produced using beehives located adjacent to or on pollinator-friendly solar sites.

Farmers can also consider direct marketing vs. wholesaling the products from the site, which can affect economics as well as logistics. For example, a small half-acre plot of fingerling potatoes sold at a local farmers market could make economic sense for the farmer, whereas a half-acre of russet potatoes sold at wholesale values may not. Ensuring economic viability of the agricultural operations is an essential component of long-term success for an agrivoltaics project.

3.3.2 Additional C3 Factors Affecting Agrivoltaic Research

Research Plot Size

A key question in agrivoltaics research relates to the minimum size of the research plot within the solar array (research plots can be a subset of the overall site). If the research plot is too small, there might not be enough replications to provide robust results. Often, considering vegetation around one row of panels is not sufficient to fully capture the shading and microclimate impacts of agrivoltaics configurations that include multiple rows of panels. However, research does not need to occur throughout the entire project footprint in order to provide insights. Agrivoltaic research plot size decisions should follow best practices for the groundcover and land management type they are studying. InSPIRE project ecosystem service and pollinator research plots are generally at least two acres in size, although there are subdivisions within those plots that can be as small as 0.25 acres. Landscape-level studies evaluating stormwater management or other phenomena might require larger plot areas and are often based on a percentage of the total land area of the site. InSPIRE crop production research areas are generally at least 0.25 acres in size, whereas grazing plots are generally over two acres in size.

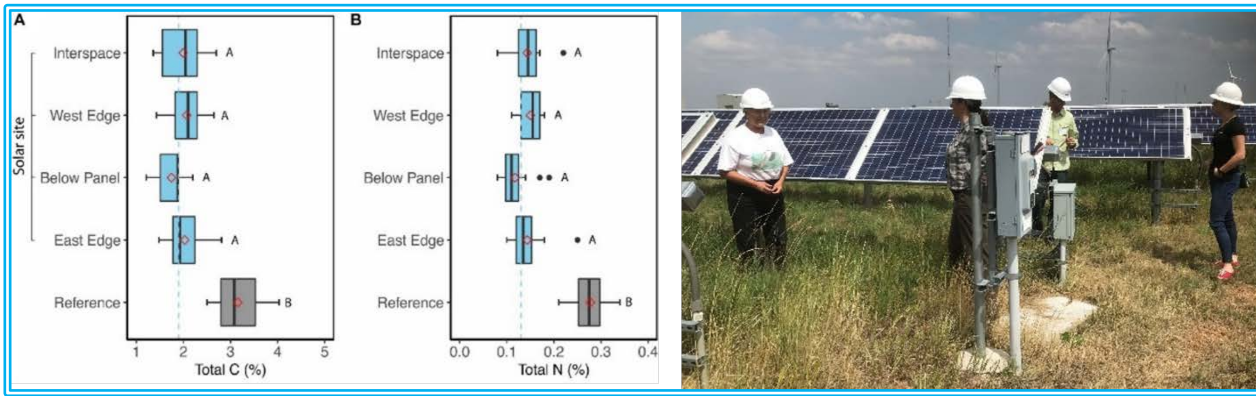
Importantly, there is inherent variability within any plot of land, which can affect research outcomes. Larger research plot areas can more easily account and control for this variability while also being more resilient to unexpected disruptions in the vegetation. If there are pests, diseases, adverse weather, or accidents that affect vegetation, larger plot sizes can still allow for sufficient data collection with the vegetation that survives. If space is limited, larger individual plot areas that account for this inherent variability could limit the number of different treatments or replicates utilized.

Duration of Research

The solar industry, and agrivoltaics as a subset, is rapidly advancing, and projects of all types are accelerating in their deployment. This creates a strong desire for quick-turnaround research that can inform future investments and deployment decisions. However, similar to agricultural research, agrivoltaics research can take multiple years, or even a decade or more, to provide robust results. Moreover, pollinator habitat and native vegetation can take 3–5 years to become fully established, and the vegetation will evolve and change over time, reflecting different grass and forb species compositions. In addition, carbon sequestration rates can change over a span of decades. Another important question is how soil responds and recovers after disturbance during construction activities; some soil characteristics are still affected nearly a decade after construction (Choi et al. 2020).

A general challenge with any agricultural research is the diversity of soil quality and conditions within a given field; there can be multiple soil types in a relatively small land area. This can lead to changes in yields or measurements that are not due to the experimental design, unless explicitly addressed. For crop production, weather patterns can affect yields and water requirements from year to year. The duration of research will in part determine what research questions can adequately be evaluated; results could differ from years 1–3 of vegetation establishment to years 4–6 and beyond. This can also change year to year, and can complicate the transferability of information and results across sites—even nearby sites.

The estimated lifetime of solar PV installations is between 20 and 30 years, which is much longer than most research studies. Researchers must consider what stage of deployment and vegetation establishment their project represents. Establishing mechanisms for obtaining funding and agreements for longer-term research projects would help with answering pressing agrivoltaics research questions.



Long-Term Soil Quality Assessments at NREL's Campus: At the NREL Flatirons Campus, InSPIRE researchers evaluated soil characteristics seven years after the site was planted with various types of native vegetation mixes for ecosystem services (Choi et al., 2020). Results showed that the land disturbed by PV construction had a diminished ability to sequester carbon and nitrogen relative to the native soil. In addition, there were variations in soil properties related to particle size and impacts from precipitation runoff from panels. An important lesson from this work is that if agricultural land is converted to a solar project, the soil quality will be affected—but intervention with vegetation early on can mitigate those impacts.

Complementing Field Work With Modeling Work

To address challenges with long-duration research in limited locations, models can be used to complement field research, helping extrapolate the impacts onto other regions or other land management practices. To date, many crop yield, vegetation growth, and ecosystem service models have not been updated to incorporate agrivoltaic conditions as rapidly as agrivoltaic deployment is occurring. Modeling efforts can inform field research design, and the results of the field work can in turn inform model development and validation efforts. One example is the work InSPIRE researchers did with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to characterize ecosystem services at solar sites across the Midwest (Figure 14) (Walston et al. 2021).

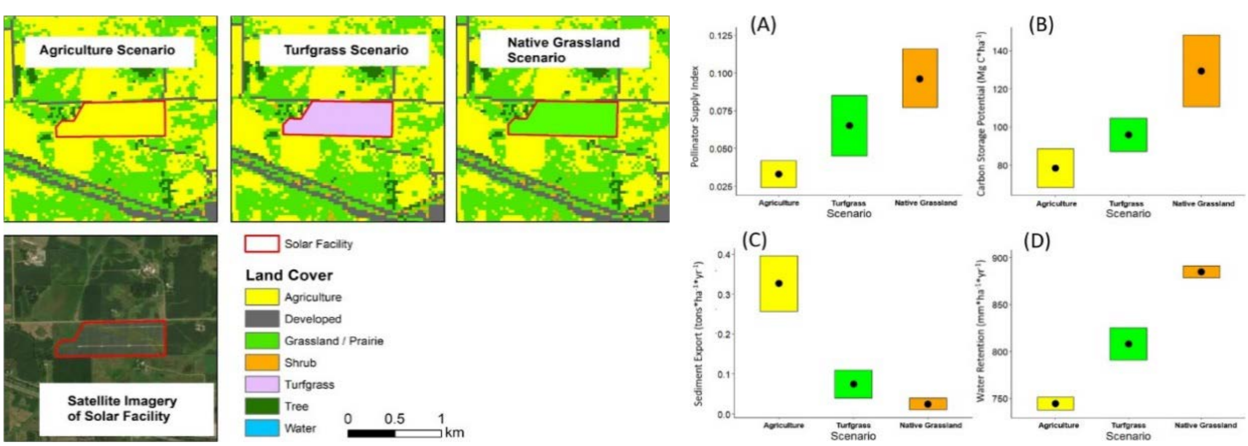


Figure 14. Ecosystem service modeling complementing InSPIRE field work.

From (Walston et al. 2021)

Control Plot Design and Representativeness

Control plots for agrivoltaic sites can generally include solar facilities with both gravel, turfgrass, or unvegetated groundcover and open-air vegetation (such as at adjacent or nearby agricultural lands, especially if the area of the solar facility was previously used for agriculture). Control plots should be as large as the core research plots whenever possible, although commercial solar project site land availability can lead to smaller control plots on the same property (Figure 15). Smaller control plots can have different conditions (related to irrigation, maintenance, and surrounding plants) than in the research site, as well as differences from commercial farming operations. Having an at-scale control plot at a different location introduces other soil and local weather factors that could also affect comparisons. In some cases, conducting "before" and "after" data collection to measure changes from baseline conditions can be used as a substitute for physical control plots.

Figure 15. Crop research control plot bed preparation at Jack's Solar Garden.

Established Research Methods

Established protocols and standard instrumentation packages should be used whenever possible for agrivoltaics research. Research protocols can be associated with agrivoltaic sites specifically or can be based on best practices in agricultural or ecosystem services research without solar, when agrivoltaics-specific methods are not established. Standard protocols and instrumentation help ensure that the data collected can be effectively shared and utilized for future projects and research (Figure 16). At times, site conditions and other project realities might lead to changes in research design, and researchers must adapt to on-site conditions.

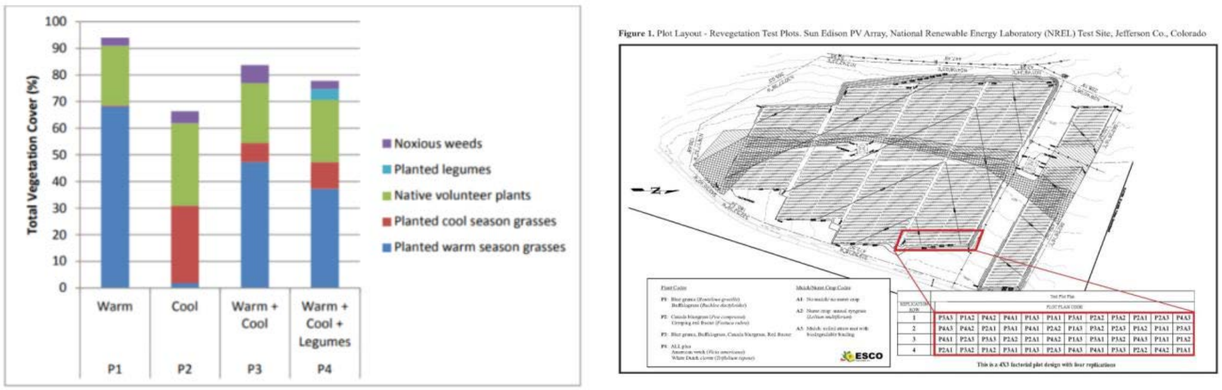
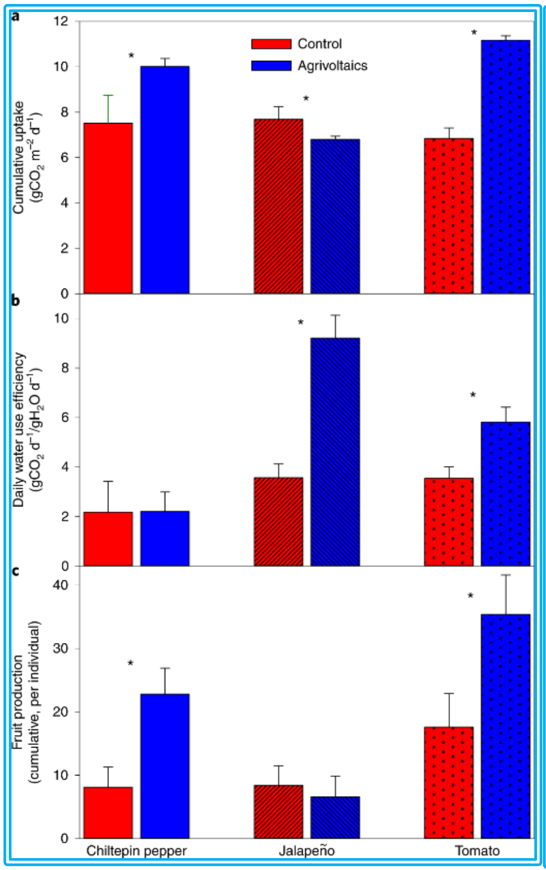


Figure 16. Research protocols and methods used by InSPIRE for vegetation assessment.

From (Beatty et al. 2017)

Common and Meaningful Metrics

As agrivoltaics projects inherently involve stakeholders from different sectors with differing priorities, collecting and reporting metrics that are meaningful to all parties can help improve the impact of the research and facilitate additional relevant research. For example, farmers might be most interested in crop yields on a per-acre or per-plant basis, sheep grazers might be most interested in available nutrition, and apiary managers might be interested in the timing of blooms throughout the year, even if these metrics are not the primary goal of the research effort. Researchers can include metrics along these lines in addition to the other metrics they are utilizing, which might focus more on plant physiology and phenology, such as photosynthesis rates, flower appearances, etc. Translating scientific metrics into practical outcomes and lessons for agricultural managers can help improve engagement and interest by all parties. Engaging farmers, landowners, and solar owners and operators early on in the research planning phase can help identify the most meaningful metrics. More recently, metrics that link to human health and social preferences are being added to agrivoltaics research projects, including details on project support, taste preferences, human and animal thermal comfort in the shade of PV panels, and consumer interests in supporting food production in agrivoltaic systems (Pascaris, Schelly, and Pearce 2020; Pascaris, Schelly, et al. 2021).



Meaningful Metrics and Research Adjustments: At the University of Arizona Biosphere2 agrivoltaics facility, InSPIRE researchers have updated and added additional metrics to the research design to ensure that research outcomes provide scientific value; these metrics include carbon uptake, photosynthetically active radiation (PAR), and daily water use efficiency. They have also included more tangible outcomes and metrics that can be used by farmers and practitioners, such as yield, soil moisture, planting and harvesting times, and germination rates. Researchers have also begun taste test trials. These additional metrics can help increase the broader impacts and understanding of agrivoltaic trade-offs beyond the scientific community (Barron-Gafford et al., 2019).

3.4 Compatibility and Flexibility (C4)

For agrivoltaics projects to be successful, the solar technology design and configuration (C2) must be compatible with agricultural and research methods (C3) as well as with the competing needs of the solar owners, solar operators, agricultural practitioners, and researchers (Figure 17).

Figure 17. Agricultural equipment at an InSPIRE research site in Massachusetts.

A summary of C4 agrivoltaic compatibility factors is shown in Table 5.

Table 5. C4 Agrivoltaic Compatibility Project Determinants

Topic	Description	Code	Agrivoltaic Type
Sitewide O&M Plans	Vegetation management plans should be customized to the specific needs of the vegetation mix that has been used at a site.	C4	All
Infrastructure Placement	The placement of solar technology infrastructure, such as inverter boxes, can interfere with worker and equipment access.	C4	All
Farm Practice Compatibility	The design of the solar installation should be compatible with desired agricultural practices on-site, including the presence of people, animals, and machinery.	C4	All
Prescribed Grazing Plans	Plans are needed to ensure that sites have the appropriate number of animals for the correct duration, while also maintaining animal health.	C4	Crop Production, Grazing
Additional Research Considerations			
Researcher Access	The ability of researchers to readily and easily access the project site and their research plots can affect the likelihood of success. Restrictions based on the timing, duration, and frequency of access could negatively affect research.	C4	All
Proximity of Site	If the research site is remote and far from the researcher's base, this could limit the researcher's ability to be on-site when needed as well as their ability to respond to any urgent situations.	C4	All
Installed Research Equipment	Research equipment should be installed in locations that are clearly marked, safe from interference by O&M crews or people on-site, and compatible with agricultural activities.	C4	All
Data Collection Compatibility	Research will be more useful and impactful if the data collection activities are consistent with common agricultural techniques and timing, such as frequency of harvesting of crops.	C4	Crop Production, Grazing
Crop Rotation Planning	Research on multi-year projects must consider crop rotation plans of commercial farming operations and the different locations of crops within a field each year.	C4	All

3.4.1 C4 Factors Affecting Agrivoltaic Project Success

Sitewide Vegetation and O&M Plans and Interactions

Even in arid, desert-like environments with degraded soils, most jurisdictions require solar installations to have sitewide vegetation management plans. The details of these plans can affect the likelihood of successful establishment and durability of the vegetation in ecosystem services projects, especially if the procedures are not aligned with vegetation needs. Some projects have different types of vegetation established in different parts of the array. This could include taller vegetation along the perimeter of the site compared with lower vegetation underneath the arrays, as well as different types of vegetation in different locations under the array. For example, some sites might drill-seed pollinator habitat between rows, but due to equipment limitations, they might have different types of seed mixes and vegetation directly underneath panels. Various types of groundcovers on-site could require different schedules for mowing or otherwise maintaining the vegetation. Depending on the overall O&M and vegetation maintenance plan for the site, this could mean changes in preferred times to mow native vegetation. Owner preferences about plant heights can also affect mowing schedules, and in some cases, this could lead to more mowing than would normally be encouraged for the vegetation type, resulting in negative consequences for vegetation establishment and ecosystem services provided. In addition, generic or overgeneralized O&M contracts might specify a mowing frequency (e.g., once per month) that results in the domination of certain groundcover species, contrary to the initially stated goals (for instance, if there was a desire for perennial low-growing groundcover that would require minimal management). Other planned O&M activities—related to vegetation control, grazing, solar equipment maintenance, additional construction, etc.—can also affect the success of vegetation, depending on the location where these activities take place and whether the activities disrupt the vegetation growth at crucial times, such as during flowering or when the plants go to seed. Although some disruption can be acceptable if it is rare, continued repetition of this type of disruption can jeopardize desired vegetation establishment.

For ecosystem services sites, a key factor is a comprehensive vegetation management plan that accommodates the intent of providing ecosystem services. For example, many of the ecosystem services provided by native vegetation depend on allowing the perennial plant species to flower and seed. However, if the plants grow to a height that shades the solar panels during the growing season, mowing or grazing will be required to maintain energy generation. Vegetation management plans can prescribe mowing or other maintenance activities during times that might affect research plots, such as when vegetation grows too high. Even if vegetation does not shade the panels, there might be precautionary policies in place related to vegetation height that would lead to mowing. This could affect research plot areas as well as control plots. Moreover, it is important that O&M service providers are aware of the research plots and know when (or when not) to mow them. If their O&M service provider changes, the new O&M providers might disrupt the research plots without clear guidance. To maximize ecosystem services, vegetation management plans should generally include planting species that will not exceed the height of the panels and that call for mowing only in late fall (except in early years, when weeds may still require control). If vegetation in some areas exceeds height restrictions during the growing season, selective mowing should be considered, including only mowing areas where vegetation is too high and potentially only adjacent to the trailing edge of panels (Figure 18). The timing of vegetation planting can also affect research outcomes. Whether the site was built over established vegetation, if vegetation was planted shortly after or during construction, or if the site retrofitted its vegetation well after project installment can affect the vegetation management plan and research outcomes.

Figure 18. Different types of vegetation under the array vs. outside of the array (top) as well as targeted mowing strips adjacent to panels to avoid panel shading (bottom) from InSPIRE research sites in Minnesota.

Communication between research teams and O&M contractors is important to ensure activities are coordinated and do not interfere with each other (i.e., a mowing event right before pollinator surveys would impact research outcomes). Organizational commitments to low-impact design and management practices, including training project developers and owners, can also influence success. Some research partners rely on the Institute for Sustainable Infrastructure to provide a credentialed training program that positively contributes to project success (Institute for Sustainable Infrastructure n.d.).

Accompanying Solar Infrastructure Placement

The placement of certain pieces of accompanying infrastructure on utility-scale solar projects (e.g., combiner boxes, inverters, batteries, grid interconnection points) can affect farming operations and the ability of equipment, machinery, people, and animals to access certain parts of the array. If the auxiliary equipment is located at the end of panel rows, for example, it could inhibit access to rows or reduce turnaround areas for equipment (Figure 19). Many sites bury cabling, but on sites with aboveground cabling, sufficient marking and safety measures need to be implemented to ensure animal and human safety. The depth of buried cabling should be deep enough to not disrupt agricultural activities, such as tilling. Fences can also limit the mobility of agricultural equipment; designs should incorporate sufficient distances between solar panels and property fences to enable equipment maneuvering.

Figure 19. Placement of solar technology equipment on an agrivoltaic site.

Farm Equipment and Agricultural Practices Compatibility

If agricultural or grazing activities require equipment, machinery, or fencing, it is essential that these items are compatible with the solar design and configuration and will not lead to solar infrastructure damage. This not only includes how farm equipment compatibility could be affected by panel heights and inter-row spacings, but also whether or not equipment (e.g., grazing fencing materials, gutters for water distribution) would need to be attached to any part of the solar infrastructure, especially moving parts of tracking systems.

In addition, during the agrivoltaic system design phase, developers should consider the types of agricultural practices that will or could be employed on each site based on its expected agricultural activity, and whether these practices would be compatible with solar infrastructure. As one example, many irrigation systems require zones of equal size and/or straight or rectangular designs in order to maintain irrigation pressure throughout the different zones; solar projects with uneven borders or rows of different sizes could lead to challenges in designing compatible irrigation systems. Irrigation equipment could also include aboveground pumping stations, water lines, and on/off valves, which could be damaged by solar maintenance vehicles or limit farmer mobility if not properly designed and protected (Figure 20).

Figure 20. Irrigation equipment and infrastructure at an InSPIRE agrivoltaics site that can affect farm equipment access.

Many agrivoltaic projects to date in the United States have been driven by solar developers, not necessarily by farmer needs, and farmers' operational preferences have not always been considered in the design. This trend could pose a challenge for finding willing farmer partners and for the project's long-term success. Traditional farming practices might not be possible unless the system is custom-designed in conjunction with farmers. Beyond the design of the array, the land itself must have all the necessary infrastructure to support the farmers' operation (e.g., cold storage, dry storage, wash areas, etc.) to allow for efficient farming. Also, many farmers can be risk averse and might only take on the "risk" of agrivoltaics if it has been proven to add benefits (increased yields, water conservation, etc.) to their specific crops in their region. Agrivoltaic projects that invite other farmers on-site to examine operations could facilitate greater farmer acceptance and adoption of agrivoltaics.

Prescribed Grazing Plans

Every solar facility under consideration for grazing should develop a Prescribed Grazing Plan (PGP, or strategic grazing plan). Each PGP will create a framework for the grazing partners to follow during a solar facility's operation, and to aid in planning. Graziers should use the PGPs to gauge their stocking rates, their timing of the graze and rest periods, the class of animals used, vegetation standards, soil conditions, and other details of the livestock management. Following the PGP, including regular forage testing, can provide a grazing partner with feedback during and in between each season. This planning and feedback steers graziers towards practices that will result in healthier plant communities and healthier soils: reducing the risk of erosion and overgrazing. PGPs should guide grazing partners to determine how much grazing versus mechanical treatment is needed at a facility, which leads to more predictable vegetation management. Prescribed Grazing Plans can be found on the American Solar Grazing Association's website as well as with the USDA National Resource Conservation Service's Pasture Condition Scoresheet (Figure 21) (American Solar Grazing Association 2022; U.S. Department of Agriculture n.d.).

Figure 21. Sheep grazing on a solar array according to a prescribed grazing plan developed by the American Solar Grazing Association.

3.4.2 Additional C4 Factors Affecting Agrivoltaic Research

Researcher Access

Research can be challenging if there are not clear pathways and entry points for researchers to access research plots without disturbing the site or negatively affecting the plots. Design of the research plots should incorporate clearly defined access points and should be communicated upfront with the site owner and operator. Researchers, site owners, practitioners, and operators also need to agree on access rules and timing for entering commercial solar sites, which are often enclosed by locked fences; this could entail safety training or signed agreements. Preparing a detailed research plan that includes points of contact and approximate frequencies and dates of planned on-site activities throughout the life of the project is key during project conception.

Proximity of Research Site

The distance of the site from the researcher's base location could affect the type of research and oversight that is possible. Locations that are further away could mean a lower frequency of visits from the researcher and/or shorter durations of on-site research activities as well as less of a presence on-site in the event of any unexpected changes. If timing is important for research (e.g., for pollinator habitat blooming, insect migration, crop harvesting), then distance could affect the ability of the researchers to be on-site at the right time.

Partnering with a local research institution, state agency, skilled vegetation contractor, or conservation organization may help address proximity limitations when the primary researcher is located a significant distance away from the research site. Establishing contracts and training students or other researchers will require significant effort and lead time that needs to be considered in project planning and budgeting.

Installed Research Equipment

Production farming often involves larger equipment and machinery for soil preparation and maintenance, which could be used for tilling, bed-making, seeding, mowing, or harvesting. Research equipment (e.g., soil moisture sensors, weather stations) buried underground or installed aboveground could be dangerous for the farmer and vegetation manager, and could also be damaged by farming equipment or other operations such as mowing. Research equipment might need to be removable or somehow protected from farm equipment that will be used on-site at certain times of the year.

Research equipment for wildlife monitoring is generally installed on tripods aboveground (e.g., wildlife motion-activated cameras, acoustic or ultrasonic monitors. Research equipment should be placed to minimize interference with site operations and be clearly demarcated to avoid accidental disturbance (Figure 22).

Figure 22. Installed research equipment on a crop production site (left) and wildlife monitoring equipment (right). Equipment can be removed during certain times of the year to enable site maintenance.

Data Collection Compatibility

It is essential that data collection and reporting activities align with farmer activities on-site. Often, research activities must accommodate the realities of farm operations. This might mean harvesting more frequently or on different days than planned based on when crops are ripe, or adjusting activities in anticipation of a coming frost. It also means that the approach to data collection should be consistent with the mechanisms utilized for harvesting. For example, harvest data might not be able to be collected on a plant-by-plant basis if harvesting operations involve machinery or other processes that don't allow for measuring yields on a per-plant basis (Figure 23). Data collection for research purposes can also be time-consuming for farmers.

Figure 23. Data collection and measurement accompanying harvests of kale at an InSPIRE agrivoltaics site in Colorado.

Crop Rotation Planning Within the Agrivoltaics Array

Agrivoltaic farmers may want to rotate crops or grow different crops each year in each bed within the agrivoltaic array, due to crop disease concerns and market considerations. This can affect the consistency of the research design, the research plot, and the control plot, and make soil and shading conditions slightly different each year. Research designs need to take into account the need for crop rotations within the array, and the inherent variability this can cause. These plans, along with other changes in vegetation or crop plans that could affect stormwater management, should be clearly communicated and agreed upon ahead of time.

3.5 Collaboration and Partnerships (C5)

Understandings and agreements made across stakeholders and sectors to support agrivoltaic installations and research, including community engagement, permitting, and legal agreements, can have an important impact on agrivoltaic project success. Agrivoltaic research naturally involves multiple partners from different sectors working together. This can include solar developers and operators, vegetation management companies, farmers, regulatory agencies, and researchers (Figure 24). Each of these stakeholders likely has different priorities and expectations, which can affect both the agrivoltaic project’s success and research activities.

Education and clear communication are key to addressing issues that might arise among partners. Unsuccessful agrivoltaic projects and those that do not strengthen local economies could have negative impacts on future agrivoltaic development, as well as utility-scale solar more broadly.

Figure 24. Agrivoltaic engagement and discussions with multiple stakeholder groups at InSPIRE research sites.

A summary of C5 factors is shown in Table 6.

Table 6. C5 Collaboration and Partnership Determinants

Topic	Description	Code	Application
Understanding Multiple Priorities and Establishing Common Goals	Agrivoltaic projects involve multiple stakeholders from different sectors with varied priorities. Understanding these priorities upfront and establishing common goals is important to a successful partnership.	C5	All
Clear Roles and Responsibilities	Agreeing to clear roles and responsibilities for each party upfront can lead to more successful agrivoltaic operations and partnerships.	C5	All
Information Sharing	Maintaining regular communication and establishing a mechanism for sharing relevant research insights, on-site O&M changes, and any other factors can help long-term partnerships.	C5	All
Long-Term Ownership and Personnel Consistency	Solar developers of agrivoltaic projects are often different from long-term operators, and site ownership can change. It is essential for agreements to include persistence of research, agrivoltaic activities, and O&M practices even after ownership and personnel changes.	C5	All
Compromises on Groundcover for Immediate vs. Long-Term Results	Some agrivoltaic installations can take multiple years to establish, which can be at odds with desires for more immediate results. Some companies might be hesitant to fully implement diverse seed mixes and supporting management	C5	All

Topic	Description	Code	Application
	practices due to uncertainties and lack of experience.		
Farmer Bandwidth, Flexibility, and Adaptations	Recognizing that farming activities might not be designed for academic research and data collection and being flexible in research approaches that are adaptable to farmer realities can improve agricultural partnerships.	C5	All
Community and Stakeholder Engagement	Early and extensive engagement with the local community about the goals and potential impacts of the project can improve overall project success and support.	C5	All
Planning, Permitting, and Zoning	Aligning on-site activities with local regulations related to acceptable land-use activities is essential to conducting agrivoltaic activities.	C5	All
Additional Research Considerations			
Communication and Signage	Having regular, clear communication pathways among the researchers, site operators and owners, O&M teams, and vegetation management contractors, including clear and legible signs to outline research areas, can help ensure that research plots are not unintentionally damaged.	C5	All
Cross-Trained Personnel	Ensuring that researchers understand agricultural practices and solar energy basics, agricultural providers understand the research methods and solar energy basics, and the solar owner and operator teams understand research goals and agricultural activities can help improve research outcomes and impact.	C5	All

3.5.1 C5 Factors Affecting Agrivoltaic Project Success

Balancing Multiple Stakeholder Priorities and Establishing Common Goals

Agrivoltaics research projects can include multiple types of project partners on-site, as well as interactions with stakeholders off site. With multiple stakeholders involved on-site, it is essential to understand the priorities of each individual partner and establish common priorities for conducting the agrivoltaics operations and research. As an example, solar energy developers generally prioritize cost-effective and sustainable energy generation, whereas agricultural partners prioritize food and animal production, and researchers have an interest in collecting and publishing data. Each site is different, with varying limitations on available land and financial resources. Grid-connected and off-grid systems can have substantially different priorities. Discussions of these priorities as early as possible during site design and construction may result in better solar design and vegetation planting configurations that optimize all on-site stakeholder priorities. Ideally, the research team, solar developers, solar operators, and agrivoltaic practitioners will coordinate early on in the site development process to establish individual and common goals. Written agreements can facilitate more effective outcomes.

Understanding the goals of each partner also allows for a unique opportunity to address perceived risks (by the solar developer or agricultural providers) through research. Addressing perceived risks related to vegetation, on-site researcher safety, costs, and other factors through the research design can provide useful data for the broader community while alleviating partner concerns. As an example, solar companies and insurance agencies might have concerns about the presence of vegetation underneath the arrays, even if these concerns and risks are not established in the literature or based on prior experience. Solar developers might also have concerns about how vegetation could disrupt permitting applications, affect fire risks, create unwanted habitat for threatened and endangered species within the array that would lead to additional costs, or otherwise affect insurance rates. These potential risk factors have not been documented or validated by research, but lack of experience among partners can affect project decisions in multiple ways, only some of which are related to agrivoltaic research or activities. Identifying ways to incorporate relevant research activities that address these concerns could help alleviate some risks and provide greater value to the solar owner and operator.

Costs for vegetation establishment and management throughout the lifetime of a solar array are minimal, usually accounting for less than 1% of installed costs for an ecosystem service project (Horowitz et al. 2020). Thus, the cost difference between a groundcover seed mix required to finalize a stormwater permit and a seed mix that also provides incremental ecosystem service benefits represents an even smaller fraction of system costs. This also implies that vegetation and groundcover options are a relatively minor component of solar project decision-making for many sites and might not be as urgent as other decisions. More plainly, making design changes to accommodate alternative vegetation options might be low on the priority list for some companies and could affect the likelihood of agrivoltaic activities being adopted.

Solar companies might also have questions or concerns about the costs of elevating panels or making other accommodations for agrivoltaics activities and research. For elevating panels, there is uncertainty for some companies with limited experience over the specific costs, as costs are affected by not only the additional cost of steel, but also design costs, local geological considerations, installation labor costs, and any additional safety precautions that must be taken. Vendors can provide substantially different estimates for elevating panels depending on these conditions, which can affect utility-scale PV profitability and economic viability. Moreover, here is also uncertainty associated with the initial cost of groundcover establishment, in addition to the potential costs associated with reseeding or management of the site to have successful establishment. In particular, the first few years of native and pollinator habitat vegetation can have variable costs. Incorporating cost analyses and reviews can help address some of these concerns. This is an active area of research, and assumptions about the directionality of the trade-offs that come with elevating panels versus the benefits of being able to conduct agrivoltaic activities are being challenged and evaluated across a range of agricultural practices and regions.

The InSPIRE advisory group, Agriculture and Solar Together: Research and Opportunities (ASTRO), was designed to help facilitate common understanding across industry, agriculture, regulatory, and research stakeholders to ensure that all sides better understand each other's priorities (Davis and Macknick 2022; National Renewable Energy Laboratory n.d.). Other research projects also have advisory groups that can provide similar feedback and a structured setting for communication.

Partner Roles and Responsibilities

When agrivoltaics involves multiple partners working on-site, including production activities and research, it is essential for there to be clearly defined roles and responsibilities. For vegetation and ecosystem services sites, clearly outlining vegetation management responsibilities and directives is essential for long-term vegetation health and for supporting ecosystem services. For crop production systems, when researchers are also harvesting, irrigating, or otherwise being active on-site, a lack of clear expectations can lead to confusion and conflict over activities that must be done on the farm by different partners. Similarly, setting clear expectations about site access throughout the array and the ability to utilize on-site equipment by different partners is essential. For grazing sites, roles and responsibilities related to water access, fence maintenance, and other factors should be clear from the beginning. Written agreements can help ensure that roles, responsibilities, and expectations are clear across all partners, which can help each partner fulfill their duties. For example, at the Jack's Solar Garden research site, the research, farming, and owner stakeholders revisit roles and responsibilities each year to improve communication and joint work efforts.

Partner Information Sharing

Because researchers and solar operators are often simultaneously collecting mutually useful information, creating a mechanism for real-time or frequent sharing of data can benefit all partners. Solar operators could share information about instances and durations of temporary power production reductions or other maintenance activities that affect normal operations. Researchers could share information on soil quality and weather data with agricultural partners. Researchers can also provide regular interim results to project participants to inform them about recent insights on vegetation performance. Developing a shared repository for updated data, recent and upcoming events, and other useful information for partners can help ensure effective communication (Figure 25).

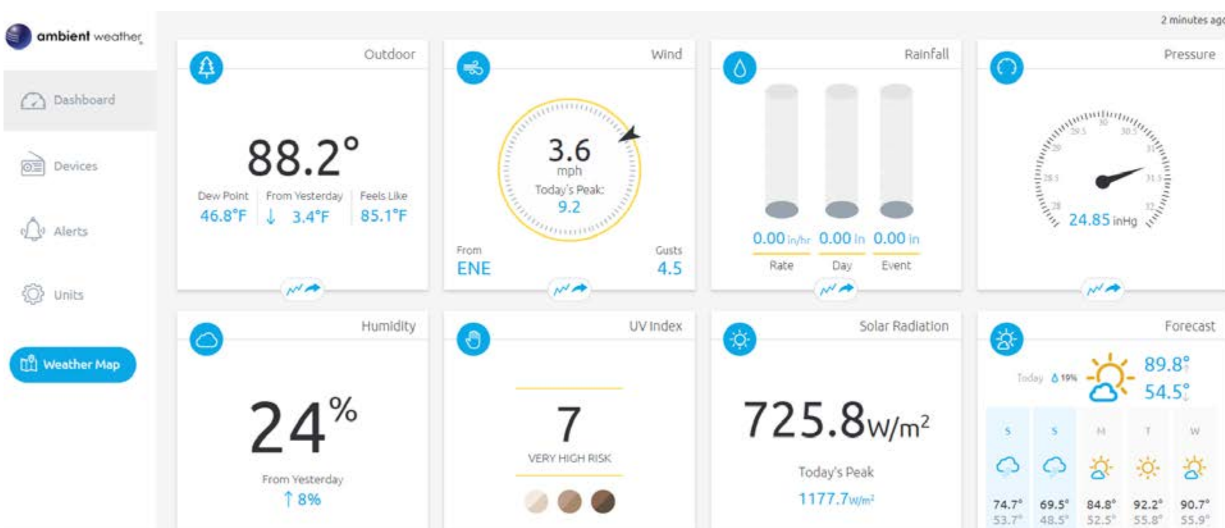


Figure 25. Shared dashboard for weather and other updates for an InSPIRE project.

Long-Term Ownership, Operation, and Personnel

Agrivoltaic activities and research require long-term commitments from host partners, as many agrivoltaic outcomes and research projects require many years to realize full benefits. However, ownership of solar projects, and the associated agreements and management plans, can change with some frequency. This means that agreements with the companies and stakeholders building the system could change if the developers do not ultimately operate the system. In addition, solar developers might have an incentive to minimize installed costs, even if those could lead to higher O&M costs, or to design configurations that make O&M more challenging to integrate with research. Research partnerships should include clauses that reflect the continuation of research under ownership and management changes.

Additionally, if O&M providers change, or if there is a dispute between the O&M providers and the site owner, it could affect the working relationship between the site and researchers, as well as overall site management. Staff turnover within a particular O&M service provider could also lead to challenges in communication and in understanding the accommodations needed for agrivoltaics and associated research. Agrivoltaic partnerships should emphasize training of new personnel on agrivoltaic and research activities. Written agreements among partners that persist even after some partners depart can help ensure consistency across ownership and personnel changes.

Groundcover Compromises and Balancing Immediate vs. Long-Term Results

Some solar developers, landowners, and vegetation management companies might want to quickly establish vegetation (e.g., for pollinator habitat) for immediate habitat results. Vegetation establishment plans might include time-saving measures such as planting plugs (i.e., small seedlings instead of seeds), for example. Farming plots might be heavily composted or fields might be tilled. However, healthy farming soils and deep-rooted vegetation can take time to become fully established, and the desire for immediate results can be in conflict with best practices for establishing vegetation. Immediate solutions could be less likely to be successful long-term, and must be weighed against the viability of the agrivoltaics and research activities. A project owner's desire for more immediate vegetation establishment results could lead to increases in installed costs as well as more labor-intensive management practices to establish and maintain that vegetation. Plugs can provide other benefits in terms of immediate soil stabilization and habitat creation in some areas. Currently, InSPIRE researchers are evaluating plugs at ecosystem services sites in Idaho and Washington, D.C., for their effectiveness in establishing long-term vegetation (Figure 26).

Some solar developers and operators prefer to utilize turfgrass and/or gravel that they have implemented on other sites without agrivoltaics, as it provides a level of cost and risk certainty. In many cases, a lack of experience with native vegetation establishment in a particular region leads to this decision. In addition, some solar and vegetation companies might not be interested in additional research into alternative vegetation approaches, as prior efforts have been deemed suitable enough. Identifying opportunities for compromises on vegetation selection and research activities can be an important part of establishing an agrivoltaic site.

Figure 26. Planting plugs for ecosystem services and beneficial habitat could accelerate vegetation establishment, albeit at a higher cost.

Community and Stakeholder Engagement

Early and extensive communication, discussions, and tours with the surrounding community to convey the goals and potential impacts of an agrivoltaic project can improve the likelihood of project success and support. Although many community members have opportunities to comment on the project during county and other permitting hearings, proactively engaging with community members can lead to greater understanding and less potential for conflict. Neighbors can also provide other assistance or support for the project if they are made aware of project needs and how the project can benefit them or their community.

The role of the public in solar development and agrivoltaic research cannot be understated. As public opposition to new forms of energy and other development increases, the consideration of a "social license to operate" rises in importance. Smith and Richards define the social license to operate as an "ongoing social contract with society that allows a project to both start and continue operating in a community. Social license to operate derives from communities' perception of a company and its operations, comprised of a company's ongoing acceptance and approval from stakeholders" (Smith and Richards 2015). Without obtaining or maintaining this social license, there can be continued conflict, controversies, or pushback in many communities. Agrivoltaics may be part of the solution to solar developers obtaining social license to operate; initial public opinion research (Pascaris, Schelly, et al. 2021) indicates that support for PV solar can increase when the PV system design incorporates agriculture.

Community engagement can lead to opportunities for cross-sectoral education and collaborative research, but it also can lead to challenges with coordinating activities and ensuring that project activities are meaningful to all partners. Stakeholder groups can include local and federal governments, K-12 and postsecondary educational organizations, landowners, solar developers, nonprofit advocacy organizations, farming organizations, agrivoltaic practitioners, and researchers (Figure 27). The diversity of stakeholders can lead to benefits such as Citizen Science opportunities, but can also have challenges associated with logistics (such as time required by site staff and researchers to support stakeholder site visits) and competing partner priorities.

For sites where research on pollinator benefits to nearby off-site agriculture is being conducted, establishing partnerships between researchers and the surrounding agricultural community and landowners is important, as research might require accessing nearby farmland, and researchers will want to be aware of current agricultural practices (Figure 27). For example, in evaluating insect populations and biodiversity, researchers will need to have access to nearby agricultural lands for comparison. In many cases, the site developer can help facilitate these connections. Alternatively, researchers can use county records to identify and reach out to local farmers and landowners to communicate their research plans and request land access. Farming organizations (e.g., trade groups like state soybean grower's associations) may also help establish relationships.

For studies of potential agricultural benefits, developing mechanisms to compensate landowners for the cost of their research participation can be very helpful in gaining access to the land needed to complete the research. Such mechanisms could include contracts or, more simply, honoraria. These should be specified and budgeted for upfront in the project contract.

Figure 27. Stakeholder meeting among researchers, developers, and citizens at an InSPIRE research site.

Farmer Bandwidth, Flexibility, and Adaptations

In cases where there is a partnership between a commercial farming organization and researchers, it is essential to note that commercial farming does not involve as much attention to monitoring and details of individual plants and crops as research farming. Farmers are often limited in time; including additional data collection activities or other burdens could take farmers away from core production activities and lead to inefficient farming practices. It is essential to find a willing farming partner who has the time to accommodate research needs, and both researchers and farmers must be flexible about setting priorities and boundaries. In some cases, this could include farmer compensation to help offset risks and time contributions.

When working on production farms with commercial farming organizations, farmer priorities (production and quality) might differ from research priorities, and farmers might adapt practices throughout the year based on weather or other factors to increase yields. This might not match ideal, controlled conditions for conducting research, and following the farmer's methods can make agrivoltaics research more complicated or produce results that are less clear. Farming activity complications might include changing when certain plants are planted or harvested, addressing pest and disease issues, preparing for frosts, and strategic harvesting based on market demands and distribution mechanisms. All of these factors can affect control plot and research plot outcomes and comparisons. Building solar projects around agricultural operations with existing vegetation and crops (e.g., coffee or fruit trees) must also minimize impacts on and potential damage to existing plants and farming operations.

Planning, Permitting, and Zoning

Project teams must ensure that the proposed agrivoltaic activities, including adaptations and changes that might occur throughout the duration of the project, are aligned and follow local permitting and zoning regulations. Permitting, zoning, and other regulations can differ from state to state, as well across counties within a state. Discussions early on with regulatory agencies can help facilitate any changes in statutes or other necessary modifications to enable agrivoltaic project development. In our exploration of shade-grown coffee in an agrivoltaic configuration in Puerto Rico, it was essential for the team to consider how to customize system designs to meet local regulations in order to disaster-harden the agrivoltaic system to withstand the high winds and other volatile weather conditions.

3.5.2 Additional C5 Factors Affecting Agrivoltaic Research

Regular Communication and Signage

In the event of unexpected visitors on-site or changes in O&M personnel, having clear rules, lines of communication, and signage can help prevent accidental disruption of or damage to research areas. Signs installed on-site can inform O&M crews and visitors about differing O&M needs for groundcover, any areas that should be left undisturbed by vehicles or mowing equipment, and the purpose of the ongoing research (Figure 28). Clear agreements between researchers and site owners and operators can ensure that new O&M personnel are made aware of the site's unique characteristics. Establishing regular check-in meetings among partners can give researchers advance notice of any upcoming changes in O&M plans that could affect their research. InSPIRE teams also have shared calendars that indicate dates of expected visitors, O&M crews, or other factors that could potentially disrupt operations.

Figure 28. Research plot signage and delineations at InSPIRE research sites.

Cross-Trained Personnel

Agrivoltaic research requires expertise in many areas, including research, commercial farming, entomology, and land restoration and management. Depending on the size of the agricultural or ecological research plots, the research activities and agricultural or vegetation management activities are often done by individuals from different sectors. Ensuring that those conducting the research and those doing the farming and vegetation management activities are properly trained on-site, are following relevant farming and vegetation management protocols while also supporting research protocols, and are aware of each other's activities and protocols can lead to fewer mistakes, improved agricultural and ecosystem services outcomes, and better research results (Figure 29). Training and educating solar owners and operators on agricultural practices and research methods can also lead to better understanding across groups. Compensating researchers and farm and vegetation management personnel appropriately can also improve outcomes.

Figure 29. Training agrivoltaic researchers and solar industry representatives on ecological vegetation management principles at an InSPIRE site in Minnesota.

4 Growing Agrivoltaics Research

The lessons learned from InSPIRE field research efforts can be built upon to support more successful agrivoltaics projects and more productive research activities going forward. These activities align with and build upon the 5 Cs described throughout this summary, and can help support the growth of agrivoltaic research activities more broadly.

Developing innovative solar technology designs and configurations

Expanding agrivoltaic field research to consider additional novel PV technologies and configurations could enable the discovery of additional synergies and mutual benefits. More studies on bifacial and semi-translucent panels in other geographic locations with additional vegetation types could address existing gaps related to microclimate and solar resource interactions. Moreover, examining unique configurations that are designed to integrate more seamlessly with current farming practices and ecosystem service goals would address practical challenges associated with previous agrivoltaic installations. More detailed cost estimates, trade-offs, and designs for traditional agrivoltaics configurations would also benefit industry and agricultural partners in decision-making. Solar technology configurations, including materials, panel height, inter-panel spacing, and inter-row spacing, should be considered holistically to better understand how they combine to alter vegetation and human outcomes.

Adopting Compatible, Flexible, and Iterative Research Approaches

Solar projects that include agrivoltaic accommodations for agrivoltaic activities and research from the beginning can be more successful in facilitating the success of both agricultural production and research, as it can be challenging to retrofit sites. Successful and widely applicable research on commercial agrivoltaic solar sites might require an iterative approach to best understand how research elements can be integrated in ways that are not disruptive to agricultural and solar operations. Researchers must be willing and able to adapt research to changing on-site realities and emerging research gaps. This includes adapting to what is physically possible on the site as well as what owners and operators will allow. In most cases, research will not be the only driver of solar project decisions. To advance research across agrivoltaic opportunities, the same site can be used for multiple research questions and purposes.

Standardizing Research Methods and Agrivoltaics Approaches

Common and universally accepted research protocols enable better science and more opportunities for collaboration, data sharing, and transferable insights. Developing and adopting standard protocols across agrivoltaic research sites can further these aims. The InSPIRE project is embarking on an activity to codify research protocols to address specific research questions. We assume, based on experience, that standardization of designs and components will also play an important role in increasing the cost-effectiveness of agrivoltaics installations, especially in small projects and specific agricultural sectors where agrivoltaic systems currently need to be custom-designed.

Establishing Effective and Mutually Beneficial Partnerships

It is essential to establish priorities, common goals, roles and responsibilities, communication norms, and contingency plans at the start of project and research development. The priorities of solar developers, landowners, farmers, graziers, and regulatory agencies might be different from the proposed research questions or key scientific gaps. Agrivoltaic projects inherently involve multiple sectors and stakeholders, making partnerships one of the most important determinants of success.

Conducting Long-Term Field Studies

As agrivoltaic projects expand nationally and globally, there is ample opportunity to continue long-term research at existing sites. These foundational studies can provide essential information about long-term impacts of agrivoltaics. Outcomes from long-term sites will improve investment and design decisions on new sites.

Intensifying Collaborative Multi-Sector Research

Agrivoltaics involves multiple sectors of research, including energy production and efficiency, soil science, ecology, hydrology, botany, agronomy, and entomology. Each project site can likely include research activities from multiple partners, enabling more comprehensive research on each site. Including more partners can increase the complexity of site logistics, but it can also lead to improved research outcomes.

Expanding the Geographic Diversity of Agrivoltaic Projects

New projects in more locations can help create new data sets and better understanding of agrivoltaic trade-offs while also helping to validate agrivoltaic models. Especially in arid regions, agrivoltaics can enable agricultural activities and vegetation growth where they are currently not viable. Exploring geographic limitations of agrivoltaics could lead to important insights related to agricultural adaptation to climate change.

Generalizing From Site-Specific to Broad Outcomes

As the number of agrivoltaic sites increases and more information is collected from longer-term sites, concerted efforts should focus on appropriately combining and comparing results to obtain more generalized information that is applicable across regions and vegetation types. Agrivoltaic outcomes depend heavily on site-specific features, and further value could be provided by synthesizing ongoing research results.

Sharing Data Nationally and Internationally

Creating shared data platforms and resources that developers, practitioners, and researchers can access will help accelerate research outcomes, which can improve deployment decisions and the success of investments in agrivoltaics.

Prioritizing Diversity, Equity, and Inclusion in Research and Partnerships

Engaging diverse audiences, including, for example, organizations that engage veterans, organizations that work primarily with minorities and/or immigrants, female-led farmers and organizations, local and community representative farmers, and Native American tribes, will enable additional perspectives and applications of agrivoltaics that are tailored to communities that could directly benefit from agrivoltaic advances.

5 Conclusions

We can build upon the successes and failures of prior agrivoltaic projects to inform new innovations as agrivoltaic projects continue to be deployed globally. This report represents a synthesis of lessons learned from agrivoltaic research field sites located across the United States as part of the InSPIRE project. The projects considered represent a diverse mix of geographies, agrivoltaic activities, and technology configurations. In this report, we have provided a list of features that contribute to the success of agrivoltaic installations and research projects, with partnerships playing a crucial role in both. We found that installation and research project successes can depend on (a) ambient climate and environmental conditions; (b) solar technology designs and configurations; (c) methods employed for selecting and growing vegetation and conducting research; (d) compatibility of installations with solar and agricultural activities; and (e) partnership arrangements. We suggest future research activities that align with these core principles as well as other approaches to grow agrivoltaic research efforts globally.

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