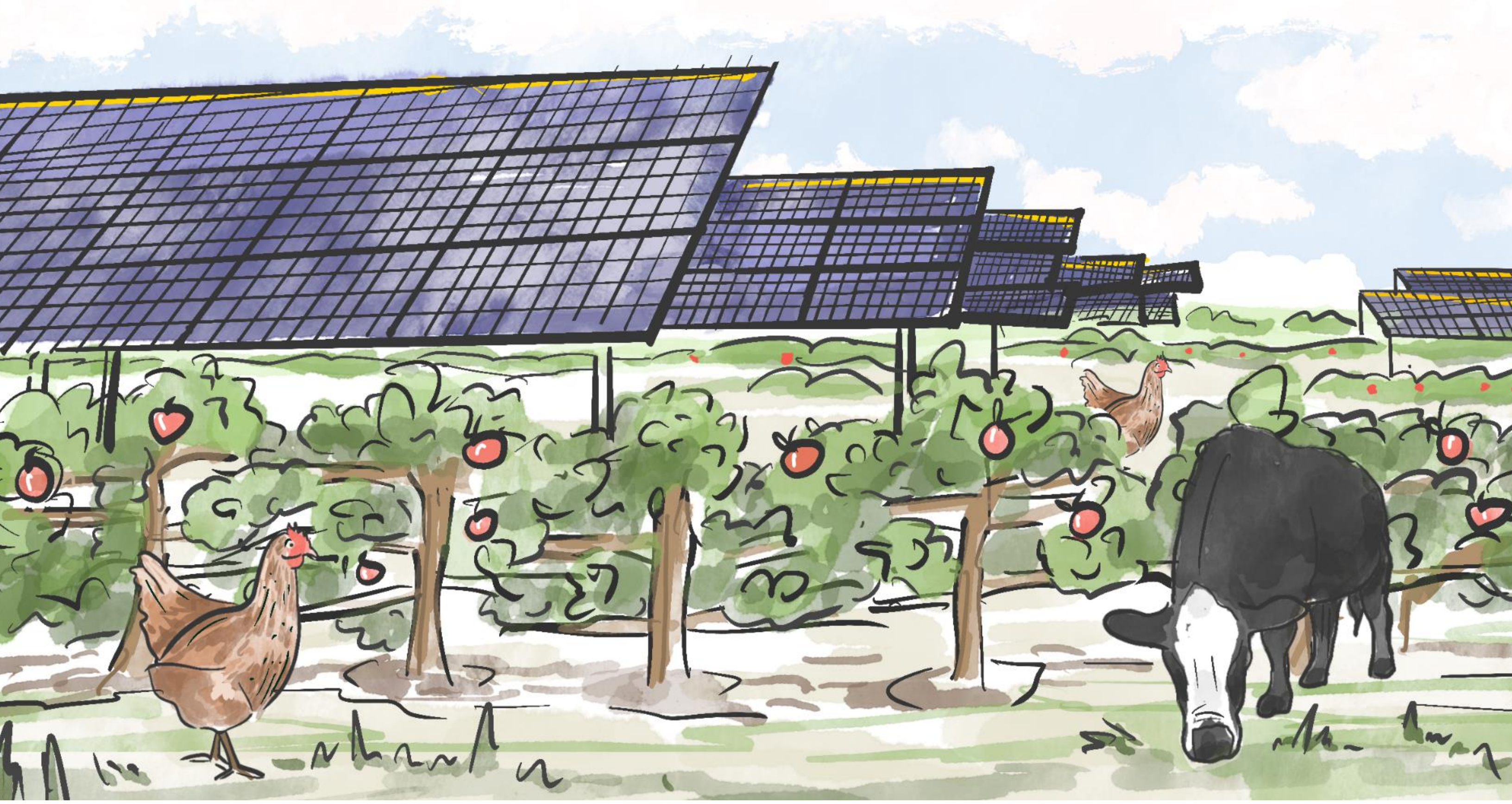
Low hanging fruit for Washington's energy future?

Agrivoltaic feasibility for agricultural and energy resilience in the Evergreen State



American Farmland Trust
SAVING THE LAND THAT SUSTAINS US
WSU TRI-CITIES Institute for Northwest Energy Futures
The Nature Conservancy
UC SANTA BARBARA

Max R. Lambert[1], Addie Candib[2], Grace Wu[3], Riley Tinianov[3], Karina Schoenbachler[4], Jamie Robertson[1], Nicholas Altadonna[1], Md. Redwan Ahmad Khan[5], Kirti Rajagopalan[5], Matt Yourek[5], Lilly Fink Shapiro[2], Austin Kinzer[2], and Chad Kruger[6,7,8]

[1]The Nature Conservancy, Washington State
[2]American Farmland Trust
[3]Spatial Climate Solutions Lab, University of California, Santa Barbara
[4]College of Agricultural, Human, and Natural Resource Sciences, Washington State University
[5] Department of Biological Systems Engineering, Washington State University
[6]Tree Fruit Research & Extension Center, Washington State University
[7]Center for Sustaining Agriculture & Natural Resources, Washington State University
[8]Institute for Northwest Energy Futures, Washington State University

Suggested Citation

Lambert, M. R., Candib, A., Wu, G., Tinianov, R., Schoenbachler, K., Robertson, J., Altadonna, N., Khan, M. R. A., Rajagopalan, K., Yourek, M., Shapiro, L. F., Kinzer, A., and C. Kruger. 2025. Low hanging fruit for Washington's energy future? Agrivoltaic feasibility for agricultural and energy resilience in the Evergreen State. Report to the Washington Department of Commerce, Olympia, WA.

Acknowledgements

This work was funded through an award from the Washington Department of Commerce (contract 24-53901-007) and The Nature Conservancy of Washington State. We are grateful to the many farmers who replied to our survey and to the farmers who we discussed agrivoltaics with. Particular thanks to Austin Allred, Freddy Arredondo, Andrew Byer, Mia Devine, Chris Henderson, Jamese Kwele, Nick Martinez, Danielle Miles, Andrew Nelson, Cathy Satava, Kirk Shroyer, Shane Stonemetz, Shanna Visser, Ray Williams, and Joe Zamboldi for discussions on farming and solar energy. This work would not have been possible without support from Cindy Pessoni, Meredith Sibley, Brandon Cox, Elliott Hong, Amanda Miller, and Sean Mertens.

Executive Summary

Washington has ambitious renewable energy goals that include developing solar energy across hundreds of thousands of acres. Deploying that solar energy while minimizing impacts to farmland and natural land and also preserving Indigenous rights is a substantial challenge. "*Agrivoltaics*" refers to installing solar arrays on farmland in a manner that allows for the continued production of crops or livestock beneath or between solar panels. This approach presents an opportunity to build much needed renewable energy while keeping farmland in production and diversifying farmers' revenue streams.

We assessed the feasibility of agrivoltaics in Washington from a technical and social perspective using a multipronged approach. First, we synthesized the global body of science to-date on agrivoltaics, interpreting that research in the Washington context. Second, we mapped Washington's agricultural lands to understand how much land might be easily suitable for agrivoltaics statewide. Third, we developed a novel modeling approach that merges property-level solar array design with crop growth to assess how we can design agrivoltaic systems. This approach allowed us to understand what the consequences might be from agrivoltaics to crop yield and quality, particularly for one of Washington's most valuable crops – apples. And fourth, we surveyed farmers across the state to understand their knowledge of and interest in solar energy and agrivoltaics specifically. This included qualitative interviews with farmers and other interested parties to understand opportunities and potential barriers to adopting agrivoltaics. We also included 'case studies' based on conversations with growers who shared thoughts about how agrivoltaics might operate in their sector. This integrated work provides an initial assessment on the biological, geographic, and social potential of agrivoltaics in Washington, laying the groundwork for further research and implementation.

The weight of the best available science suggests that perennial fruiting crops (apples, berries, etc.) are particularly amenable to agrivoltaic systems. Many vegetable crops like leafy greens, crucifers (broccoli, kale, etc.), and nightshades (tomatoes, peppers, eggplants, etc.) have variable success under agrivoltaic systems that depends on variety, system design, irrigation, local environment, and other conditions. Although some research provides tantalizing evidence that agrivoltaics will be feasible in Washington, additional science (e.g., on crop types, agrivoltaic designs) would enhance successful agrivoltaics uptake in a manner that supports farmers' needs and the state's energy goals. Importantly, although scientific research relevant to Washington is currently limited, the broader body of agrivoltaic literature is growing. As such, as science advances, conclusions in this report may change. Ideally, research will occur in Washington to better develop our understanding of how well agrivoltaics can be deployed.

Based on our mapping, agrivoltaics has the potential to make substantial inroads into Washington's long-term energy demands that are projected to double by 2046. Although most land in Washington near substations is some form of agriculture, proportionally little of that farmland is amenable for agrivoltaics. Even so, we identified over 204,000 acres of land in Washington that is hypothetically amenable for agrivoltaics given crop types, degree of irrigation, and proximity to substations. If those acres were fully built out, this amount of land could hypothetically equal 20.5 - 41 GW of solar energy. However, over half of the potential agrivoltaic land near substations is pastureland.

Under more reasonable assumptions around how much pastureland can be converted to agrivoltaics, we identified nearly 87,000 acres of cropland and pastureland amenable for agrivoltaics, equaling 8.7 - 17.4 GW of potential solar energy capacity from agrivoltaics. In this more plausible scenario, pastureland represents less than 10% of agrivoltaic acreage in Washington. In contrast, orchards represent roughly 50% of all potential agrivoltaic acreage in the state, with nearly all of it falling in central and eastern Washington. 15% of the statewide agrivoltaic potential occurs in land classified as berry, vegetable, or vineyard with most of the berry potential in western Washington and most of the vineyard and vegetable potential in eastern Washington. However, much of the vineyard and berry harvest in Washington relies on machines that straddle crop rows, thus prohibiting agrivoltaic use without adapting solar technology, farm machinery, and farming practices. Grant, Yakima, and Benton counties have the largest cumulative area of potential agrivoltaic acreage. Further, multiple counties have over 2,000 acres of orchard within 1-mile of a substation: Grant, Chelan, Yakima, Douglas, Benton, Okanogan, Franklin, and Walla Walla. Within the Columbia River Basin, we estimate that Washington has over 2.5X the potential agrivoltaic acreage than Oregon and over 7X that of Idaho, suggesting that Washington is uniquely poised to develop agrivoltaics at scale.

A more ambitious energy siting scenario that considers agrivoltaic development within 1-mile of transmission lines (rather than substations) identifies over 350,000 acres or 35-70 GW of solar power. This acreage includes over 145,000 acres (15-30 GW) of orchards in central and eastern Washington and over 13,000 acres (1.3-2.7 GW) of berries in western Washington. The acreage of potential agrivoltaic land within 1-mile of transmission is 4.5X the acreage of potential agrivoltaic land within 1-mile of substations, although this acreage overestimates how many projects can directly tie into transmission.

Besides pasture, it is noteworthy that crop systems that are compatible with agrivoltaics are not the dominant agricultural land areas. Over 25% of agricultural land statewide – and 32% of eastern Washington agricultural land – within 1-mile of substations is cereal grain. Another ~15% of land statewide – and 34% of land in western Washington – is hay or silage. This is important because the mechanization inherent to cereal, hay, and silage production is incompatible for agrivoltaics given current machinery and farm practices. The scale of these land uses in proximity to substations underscores the likely tension between this form of agriculture and solar energy development. Specifically, although this cereal grain within 1-mile of substations represents less than 5% of the state's cereal grain production, it could yield approximately 18-36 GW of solar power but without maintaining agricultural production beneath solar panels.

We also explored colocating solar arrays on pivot corners, the often-underutilized area of farmland outside of a center pivot-irrigated field. We identified over 40,000 acres of pivot corner within 1-mile of substations, representing 4.4 - 8.7 GW of potential solar power. Solar on pivot corners could therefore represent a significant contribution to Washington's energy future that is socially and technologically simpler to deploy than agrivoltaics. Even so, the land area and energy potential for pivot corners is half of what we conservatively estimated for agrivoltaics. As such, agrivoltaics and pivot corners – along with other forms of colocation – may provide complementary paths forward for non-emitting energy from Washington farmland.

We provide an interactive web map that allows users to explore amenable agrivoltaic farmland and pivot corners within various distances of substations and transmission lines.

Our agrivoltaic modeling demonstrates that crop-based agrivoltaics can be feasibly evaluated at the property scale and across Washington's diverse climates, providing estimates of solar energy production, system costs, and impacts to crops. We found that lettuce is a promising candidate for agrivoltaic deployment in Washington, with average yield reductions under solar panels of less than 10%, and some regions showing as little as 3% loss. In contrast, strawberries are more shade-sensitive and showed yield reductions of 40–84%.

In apple orchards, elevated single-axis tracking arrays show strong potential to reduce sunburn risk by 34–95%, depending on array design and location, outperforming conventional shade cloths. While denser tracking arrays reduce sunburn more effectively, they also cause greater shading, resulting in some yield loss in apples but also a greater reduction in sunburn risk and an increase in the percent of marketable fruit. Apple agrivoltaics systems – which require elevated panel structures to rack panels above tree canopies – are more expensive than standard utility-scale ground-mounted PV, with levelized electricity costs ranging from $70–$85/MWh. However, these costs are still within the range of utility-scale solar projects in the U.S. and are comparable to projects at similar latitudes and solar radiation. The most cost-effective apple agrivoltaic systems will be in regions like Yakima, Benton, Grant, and Chelan counties. We find that well-designed agrivoltaic systems can significantly improve land use efficiency: for lettuce, agrivoltaic systems achieve land equivalency ratios of 1.7 to 1.9, meaning 1.0 acre of agrivoltaics can produce as much combined food and energy as 1.7 to 1.9 acres dedicated to either use alone. Economic analyses from other regions of the world suggest agrivoltaic projects can be viable and competitive with sufficient regulatory incentives. Additionally, although agrivoltaic projects tend to be costlier than standard ground-mounted solar projects, they are still cheaper than rooftop solar installations. Beyond our work here, no economic analyses currently exist in the Washington context.

Social science continues to show that farmers view farming as a key component of their identity and that that the solar industry threatens their identities and way of life. In contrast to standard utility-scale solar, research suggests the farming community is more optimistic about agrivoltaics allowing farming to persist and potentially thrive. We surveyed over 100 farmers across Washington and conducted in-depth stakeholder interviews to assess the perspectives, concerns, and opportunities surrounding agrivoltaics among Washington's agricultural producers. Our findings reveal a nuanced landscape of attitudes toward solar energy and agrivoltaics in Washington. The farming community tended to recognize that solar energy in general could benefit local communities but farmers, particularly in eastern Washington, also tended to believe that solar energy would harm agriculture. Even so, over half of our respondents expressed moderate to strong interest in implementing agrivoltaic systems, yet only one quarter believed such systems were feasible within their current operations. Most producers were unwilling to alter their crop types to accommodate solar infrastructure, underscoring the importance of compatibility and flexibility in agrivoltaic design. Notably, awareness of agrivoltaics among producers remains limited, with 40% of respondents unfamiliar with agrivoltaics prior to the survey. However, exposure to definitions and visual examples significantly increased receptivity, with 59% indicating willingness to host solar panels if farming could continue beneath them. Geographic differences were pronounced: producers in western Washington were generally more supportive of solar development on farmland than eastern Washington farmers. Concerns about the impact of solar siting on farmland productivity, land access, and tenant farming were widespread, with many respondents reporting direct, repeated outreach from solar developers—particularly in Eastern Washington.

Our work identified several key hurdles to agrivoltaics in Washington: high upfront costs, gaps in information and technical assistance, and a lack of accessible, region-specific proofs of concept. To address these issues, we offer eight strategies that Washington could use to increase agrivoltaic deployment in the state.

1. Invest in place-based research and demonstration projects, particularly at different Washington State University research farms
2. Provide farmers with accessible information, including through Washington State University Extension and conservation districts
3. Develop forums for agricultural producers, energy developers, and county and state regulators to collaborate and discuss opportunities
4. Explore policy pathways to incentivize agrivoltaics in Washington
5. Implement financial incentives
6. Build new energy infrastructure in places that can facilitate agrivoltaic deployment
7. Elevate opportunities for other "Smart Solar (SM)" projects where solar and crop or livestock production are integrated complimentarily, such as on pivot corners.
8. Consider public lands as opportunities for agrivoltaics.

Agrivoltaics presents a promising path forward for brokering Washington's energy future in a manner that is cost effective and land use efficient, minimizes harm to ecologically- and culturally- significant landscapes, and creates new opportunities for the state's agricultural industry. Our body of work finds that apple orchards may be especially suitable for agrivoltaics in Washington given the large acreage, synergies with the crop production, and economics. Ultimately however, substantial adoption of agrivoltaics in Washington State will depend on Washingtonians' willingness to invest in research and demonstration, cross-sector collaboration, financial incentives, and creative policy solutions.

Contents

Context

Washingtonians value protecting both agricultural and natural lands while also rapidly transitioning to a clean energy economy. Such values are codified in state laws like the Growth Management Act (GMA) and Clean Energy Transformation Act (CETA; SB 5116). These laws protect natural spaces and agricultural production from unfettered development and promise Washingtonians an energy landscape free of carbon emissions by 2045. Further, passed in 2021 and 2023 respectively, HB 1812 amended the Energy Facility Site Evaluation Council (EFSEC) mandate to encourage the development of clean energy permitting, and HB 1181 added climate goals to the GMA, requiring jurisdictions' comprehensive plans to incorporate climate elements which can include generating clean energy. Washington also has critical obligations to Tribal Nations for safeguarding cultural and natural resources. Rapidly deploying clean energy while preserving Indigenous rights and protecting agriculture and ecosystems from degradation or conversion is a formidable endeavor.

Washington's renewable energy ambitions are large, yet it lags behind the rest of the nation in deploying renewable energy at the scale needed (Schick and Samayoa 2025). How much in-state clean energy generation Washington needs is difficult to predict. One estimate suggests that Washington will need to build over 10 GW of utility-scale solar in-state by 2050, in addition to a portfolio of other in-state and imported energy generation (Net-Zero Northwest 2023). However, this analysis did not account for growing power demand (e.g., from data centers, electrification). Indeed, new estimates suggest that electricity demand throughout the northwest is likely to double in the next 20 years (Simmons et al. 2025). Importantly, none of these estimates account for potential breaching of the Lower Snake River Dams and the associated replacement energy services, as outlined by the 'Six Sovereigns' (i.e., Confederated Tribes and Bands of the Yakama Nation, Confederated Tribes of the Umatilla Indian Reservation, Confederated Tribes of the Warm Springs Reservation, Nez Perce Tribe, State of Oregon, and State of Washington; see Columbia Basin Restoration Initiative 2023). As such, Washington's in-state utility-scale solar build out is likely to be over 20 GW during the next two decades. Given 5-10 acres are needed per MW of solar generation, an energy build out of 20 GW would result in 100,000-200,000 acres of land use for solar energy generation, approximately the same acreage as covering the surface of Lake Washington ten times. More land will be consumed as energy demand grows beyond this.

One potential contribution to balancing multiple values while building out Washington's much needed clean energy is agrivoltaics. Agrivoltaics is the practice of colocating solar energy production on farmland in a manner that allows crop or livestock production beneath solar panels or between solar array rows (Figure 1). With respect to agricultural land, the current standard model of solar development is the complete conversion of land from farming to energy production, although natural landscapes are also readily being consumed for energy production. Some farmers are also opting to convert portions of their farmland to solar arrays, allowing them to continue farming on the remainder of the land. Partial conversion allows for energy production and farming on the same property but without co-producing energy and agriculture products on the same portion of land (Figure 1). Co-location that does not include converting productive farmland could include developing solar energy on pivot corners, livestock dry lots, or the roofs of large infrastructure like dairy loafing roof sheds. Solar energy production generally has the greatest potential over croplands, underscoring the inherent tension between deploying this renewable energy and protecting farmlands (Adeh et al. 2019). This is because the land is often relatively flat, already clear, sunny, inexpensive, and often close to existing energy infrastructure like transmission lines and substations. Indeed, solar energy siting on farmland has caused controversy in Washington for years (Bernton 2018, Block 2025, Zhou 2025). These tensions underscore how agrivoltaics may be enticing as a mechanism to simultaneously produce clean energy, preserve agricultural land, sustain food production, and support greater economic resilience for farmers.

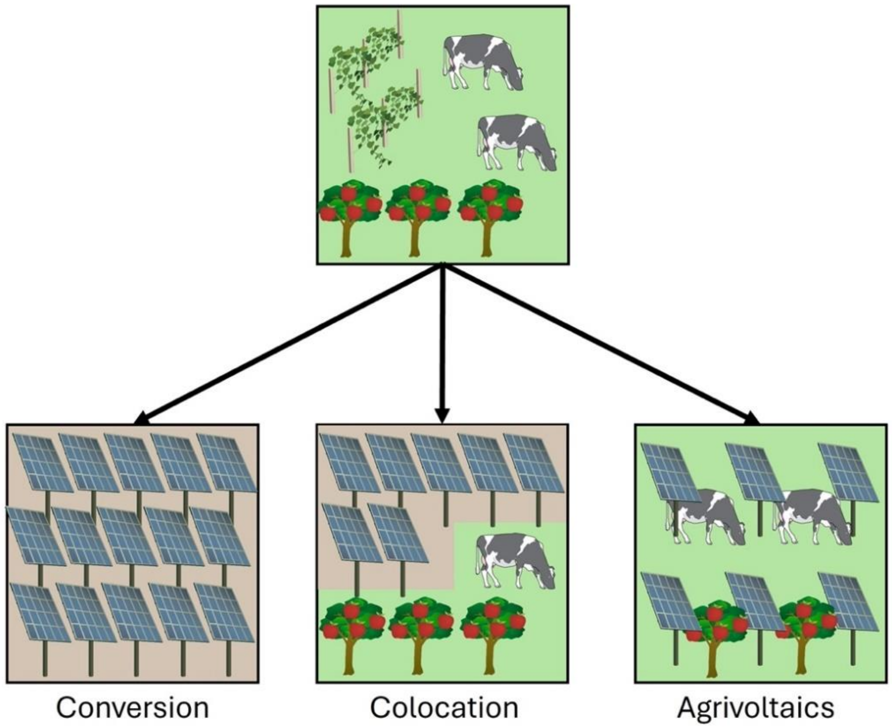


Figure 1. Farmland is a prime candidate for use in solar energy production through multiple pathways. One is a complete conversion of farmland to solar arrays, maximizing energy production at the expense of continued agricultural production. A second pathway is through colocation, where agricultural land – either land in production or unproductive land like pivot corners – undergoes partial conversion to solar arrays on a property but the rest of the property remains in agricultural production. A third pathway is agrivoltaics where solar arrays are deployed on farmland in a manner that allows for continued production of crops and/or livestock beneath and among panels. Icons provided by University of Maryland's Center for Environmental Science.

Although agrivoltaic systems typically have lower energy densities than standard utility-scale ground-mounted solar energy systems, agrivoltaics still typically yield decent solar energy densities (80-245 kW/acre). Agrivoltaics also represents tremendous land use efficiencies because the same plot of land is used for both agricultural and energy production, rather than using a larger expanse of land to accommodate both uses separately (Pandey et al. 2025). Further, agrivoltaics have the potential to facilitate or even enhance agricultural production beneath and around solar arrays. This is because the shadows cast by the solar infrastructure influence the microclimates both beneath solar panels as well as in the rows between panels (Pandey et al. 2025). Regardless of whether agrivoltaics uses a standard ground-mounted solar array height of 4.5 ft and greater row spacing or if agrivoltaics rack solar panels at greater heights, these approaches reduce sunlight penetration, increase soil moisture, and decrease air temperatures beneath panels particularly at the warmest times (Pandey et al. 2025). Agrivoltaics' local environmental effects have been repeatedly shown to reduce irrigation needs for pastures and crops. Beyond additional revenue from generation, agrivoltaics therefore may increase agricultural efficiencies.

Understanding the potential for agrivoltaics in Washington is timely because the state legislature passed SB 5445 during the 2025 legislative session to encourage distributed energy resources statewide. SB 5445 included agrivoltaics which it defines as "a ground-mounted photovoltaic solar energy system that is designed to be operated coincident with continued productive agricultural use of the land". We note that agrivoltaics is often considered both as a distributed energy resource as well as a utility-scale option. Several counties in Washington are already considering agrivoltaics. For instance, Adams County[1] recently defined agrivoltaics in its county code and Yakima County[2] is contemplating agrivoltaics[3] to moderate conflict between solar energy and agriculture. However, some counties like Benton[4], Kittitas[5], Skagit[6], and also Yakima[3] have restrictions or moratoria on siting solar energy on agricultural land, including agrivoltaics.

As a scientific concept, agrivoltaics has slowly gained traction for several decades, with an explosion of research interest over the past ~five years. In practice, agrivoltaics meaningfully began in Japan two decades ago and blossomed with the creation of a 'feed-in tariff' incentive. Japan now has roughly 2,000 small farms (0.25 acres or less) with a cumulative 1,400 acres in agrivoltaic production, contributing 1% of the country's solar energy production (Tajima and Iida 2020). Since 2000, there has been a flood of published research on agrivoltaics from demonstration sites and new university experimental stations, primarily in European and Asian countries as well as some in the eastern United States (Pandey et al. 2025). According to the National Renewable Energy Laboratory (NREL), there are few agrivoltaic projects in the western United States, particularly the Pacific Northwest. Across the U.S. the overwhelming majority agrivoltaics projects are sheep grazing under existing ground-mount solar farms and few agrivoltaic projects are testing the feasibility of marrying solar energy and crop production[7]. Even so, there are emerging agrivoltaic demonstration programs across the United States including in Oregon, Colorado, Arizona, California, New York, New Jersey, Massachusetts, Alaska, Iowa, and Ohio.

Farmland and agricultural viability in Washington State are under mounting pressure from a combination of economic, environmental, and demographic challenges. According to the U.S. Census of Agriculture, between 2017 and 2022, the state lost approximately 824,000 acres of farmland, representing over 5% of its total agricultural land. This loss is being driven by many factors, including competition from other land uses, climate change, and escalating economic challenges. Rising agricultural input costs, such as labor, fuel, fertilizer, and equipment, strain farm profitability in an industry where margins are markedly thin. Climate change is intensifying weather variability, leading to unpredictable growing seasons, water scarcity, and increased pest pressures. Compounding these issues is the aging farmer population—many of Washington's farmers are nearing retirement age, and without clear succession plans, their land is often sold or repurposed. This generational turnover is a key factor in the consolidation of farms, as smaller family-run operations are absorbed into larger agribusinesses. From 2017 to 2022, Washington lost 3,717 farms, while the average farm size increased to 432 acres. These shifts may constrain the diversity and resilience of the

[1] https://www.codepublishing.com/WA/AdamsCounty/html/AdamsCounty17/AdamsCounty1772.html
[2] https://washingtonstatestandard.com/2025/01/09/yakima-countys-two-year-ban-on-solar-may-continue/
[3] https://washingtonstatestandard.com/2025/01/09/yakima-countys-two-year-ban-on-solar-may-continue/
[4] https://bentoncountywa.municipalone.com//files/documents/BOCCPKTOA2021-00412-21-21129012930121521PM.pdf
[5] https://www.co.kittitas.wa.us/uploads/bocc/ordinances/2019-004-ordinance.pdf
[6] https://www.skagitcounty.net/Departments/PlanningAndPermit/2024AgNRLZone.htm?utm_medium=email&utm_source=govdelivery
[7] https://openei.org/wiki/InSPIRE/Agrivoltaics_Map

state's agricultural sector, making farmland protection, investments in agricultural viability, and support for new farmers more critical than ever.

Despite being among the top 15 agricultural states in the U.S. (2nd after California among the western states; Economic Research Service 2025) and having robust clean energy goals, Washington has no research or demonstration farms dedicated to agrivoltaics. Washington is the leading producer of apples, sweet cherries, pears, blueberries, and hops and the second largest producer of apricots, raspberries, grapes, and spearmint oil (National Agricultural Statistics Service 2024). The state is also among the top 10 producers of cattle, including dairy cattle with beef and dairy cattle representing the 2^{nd} and 3^{rd} most valuable agricultural commodities in Washington, after apples. Many of the commodities that form the foundation of Washington's robust agricultural economy may also be amenable to agrivoltaics. Further, central and eastern Washington may be uniquely well set up for agrivoltaics because of the sunny climate, irrigation services from the expansive Columbia River system, and existing electricity infrastructure from hydropower.

Our goal here was to begin assessing the feasibility of agrivoltaics in Washington state. We took a multipronged approach to our agrivoltaic feasibility assessment. First, we synthesized the global body of science to-date on agrivoltaics, interpreting that research in the Washington context. Second, we mapped how much land might be easily suitable for agrivoltaics across Washington. Third, we used a modeling approach that merges property-level solar array design with crop growth to assess how we can design agrivoltaic systems for different parts of Washington and understand what the consequences (positive, neutral, or negative) might be to crop yield and quality for important crops like apples, strawberries, and lettuce. Finally, we surveyed farmers across the state to assess their knowledge of and interest in solar energy in general and agrivoltaics specifically and conducted qualitative interviews with farmers and other interested parties at the agriculture-renewable energy nexus to better understand opportunities and barriers to agrivoltaics deployment. This integrated work provides an initial assessment at the biological, geographic, and social potential of agrivoltaics in Washington.

Science Synthesis

Our goal was to review the complete body of research on agrivoltaics, interpreting this global research within Washington's agricultural and climatic context. A systematic review of science is important for ensuring that conclusions (e.g., about a particular crop or about water savings) account for all relevant research, including studies that might differ in their findings. Such syntheses highlight the degree of variability in results across studies and describe the amount of (un)certainty ascribed to different issues. Doing so reduces the effects of focusing on specific studies that support a presupposed conclusion. In 2023, the Washington State University published a report on '*Dual Use Solar Opportunities for Washington State*', providing high-level context for some research pertinent to agrivoltaics (Energy Program 2023). However, this report did not assess the full body of research available on the topic. Similarly, a recent thesis explored the implementation of agrivoltaics under Washington's Growth Management Act, highlighting many policy opportunities with agrivoltaics but was unable to review the weight of the science (Smith 2025).

For our science synthesis, we capitalized on multiple agrivoltaic literature reviews that have been published in recent years. We leveraged these reviews, summarizing general conclusions shared across reviews and discussing these findings in the context of Washington. We also used the software Publish or Perish (Harzing v8) to query Google Scholar using various pairings of 'agrivoltaic' or 'agri-pv' with broad crop groups like 'berry', 'fruit', or 'vegetable' or crop types like 'apple', 'cow', or 'lettuce'. We merged results from these searches, removed duplicate entries, and searched the top-ranked results for literature that may not have been incorporated into prior literature reviews.

To focus our review on Washington's context, we emphasized research occurring in the climate classes occurring in Washington's agricultural regions, as has been done in prior research (Birchall et al. 2025, Pandey et al. 2025). To do this, in ArcGIS Pro we extracted climate zone classification data using the Koppen-Geiger system that has been used for over a century (Appendix Figure 1; Beck et al. 2018). The Koppen-Geiger system classifies the world's climate zones into five dominant climate types (tropical, arid, temperate, cold, polar) and 30 subtypes. Washington – and its agricultural regions – are dominated by four climate classes (Appendix Figure 1). Western Washington's lowlands are class 'Csb' which is defined as temperate with dry, warm (but not hot) summers. This climate type is uncommon globally but is also found along coastal Oregon and California, parts of Chile and Argentina, southern coastal Australia, the northern Iberian Peninsula, and parts of east Africa. Central Washington's mountainous region and Washington's border with Idaho are defined by the 'Dsb' climate class, which is a cold climate with dry, warm (but not hot) summers. This climate class is also relatively rare around the world, occurring mostly in parts of Oregon, Idaho, the U.S. Sierra Nevada Mountains, and in parts of Turkey and Afghanistan. Washington's Columbia Plateau is defined by two climate classes: 'Bsk' (arid, cold steppe) and 'Bwk' (arid, cold desert), both of which are characterized by cold winters with warm-to-hot summers, although Bsk has slightly higher precipitation and supports more vegetation than Bwk. These two classes are pervasive across the United States' intermountain west region, Chile and Argentina, southern Africa and Australia, large parts of central Asia (China, Mongolia, Pakistan, Kazakhstan, etc.), and parts of the Mediterranean including central Spain, southeastern Italy, Morrocco, and Algeria.

Contextualizing agrivoltaic research based on the climate it was conducted in is important to ensure that inferences from research translate to Washington's growing conditions. In addition to climate, Washington's agriculture is defined by its notable river systems which provide more sustainable water resources than in most other regions around the world where these climate classes occur, particularly in central and eastern Washington. In particular, the Columbia River system and associated irrigation infrastructure allows for a diversity of water-intensive crops in an otherwise arid system. In western Washington, large perennial river systems like the Nooksack, Skagit, Stillaguamish, Snohomish, and Chehalis Rivers have permitted western Washington's expansive agricultural areas too.

Crops and Livestock

Although agrivoltaics as a concept has been around for decades and has occurred in practice throughout the 2000's, published research remained scant until around 2020 with a marked increase in available published science (Laub et al. 2022, Pandey et al. 2025). One recent meta-analysis assessed published research both on shade and agrivoltaic impacts to crop yield in temperate and subtropical systems, assessing which crops might be shade benefitting, shade tolerant, or shade susceptible (Laub et al. 2022). Importantly, this analysis only included research that assessed shade throughout the whole growing season, rather than during the hottest portion of the year. This is important as most agrivoltaic projects provide shade throughout the year rather than specific seasons, as is the norm for shade cloths. Even so, emerging research in orchards is using artificial intelligence and tracking panels to seasonally adjust shading based on the needs of the plant at different parts of it cycle (e.g., leafing out, flowering, fruiting) (Bruno 2023).

The analysis by Laub et al. (2022) found that berries, other fruits, and fruiting vegetables (e.g., peppers and squashes) have potential to experience yield benefits with up to ~20-30% reduction in solar radiation. At up to ~20% reduction in solar radiation, forages, leafy vegetables, and root crops can be somewhat shade tolerant whereas grains, grain legumes (e.g., soy, chickpeas), and corn are the most susceptible to shading. Importantly, there are a limited studies on shade effects to various fruits and fruiting vegetables, resulting in some uncertainty about shade tolerance or benefits, particularly at higher shade levels. Laub et al. (2022) concluded that fruits and fruiting vegetables have the strongest potential for agrivoltaics while other crops like leafy greens or root vegetables have modest potential. Notably, crops like leafy greens had a high degree of variability in their responses – including positive responses – to shade and so can either tolerate or benefit from shade depending on the growing context. Although yield is a dominant consideration for producers, fruit and vegetable markets also rely on produce *quality* which was not considered by Laub et al. (2022).

Widmer et al (2024) reviewed the agrivoltaic literature with respect to crop production, climate, geography, soils, etc. This review focused strictly on studies occurring under or between solar panel rows and identified 54 studies that met their stringent criteria, most of which occurred in Europe and eastern Asia. Most research reviewed by Widmer et al. (2024) occurred with fixed-tilt, stilt mounted systems although a small number used tracking photovoltaics. Relevant to the Washington context, none of the Asian studies were in the climate zones representative of Washington, and most of the European studies were also in climate zones different from Washington. Only three studies occurred on livestock and nearly 2/3 of the studies focused on vegetables (typically lettuce and tomato) with small numbers on vineyards, orchards, berries, etc. Of the 13 lettuce agrivoltaic studies reviewed by Widmer et al. (2024), lettuce yields were typically substantially reduced or functionally equivalent to normal unshaded conditions. Yield results for the 11 tomato agrivoltaics studies reviewed were markedly variable with some studies showing substantial yield reduction, others showing yield increases of up to a doubling of fruit production, and others showing equivalent marketable yields of agrivoltaic tomato plants compared to control growing conditions. This variability is likely a function of tomato variety, climate, and other nuances that make generalization difficult. Sweet peppers showed an increase in yield under agrivoltaics whereas alliums (e.g., onion and garlic), basil, and spinach typically had decreased yields. Other vegetable crops including arugula, cabbage, broccoli, and celeriac were not typically positively or negatively influenced by solar arrays. Legumes (e.g., soy and various beans and peas) generally show decreased yields under agrivoltaics. Few fruit crops were available to review. Even so, the limited data showed some positive effects of agrivoltaics on apples and kiwifruit and negative impacts on grapes. Notably, because agrivoltaics studies differ substantially in the cultivars used and the agrivoltaic systems employed (size, orientation, tracking vs fixed, panel elevation, etc.), it is difficult to generalize how many crops will operate under an agrivoltaic system. Based on their review, Widmer et al. (2024) concluded that agrivoltaic success is variable and that, after crop type, soil and climate variation likely influence the agronomic success of an agrivoltaics.

The most recent review synthesized a broader suite of 226 agrivoltaic studies from around the globe, including prior meta-analyses and literature reviews, as well as some modeling work (Pandey et al. 2025). 100 of these studies report the PV capacity with 32 having small systems (> 100 kW), 25 having medium sized systems (100 kW – 1MW), and 43 having large systems with 1 MW capacity or higher. Pandey et al. (2025) use the Koppen-Geiger climate zone classification to stratify conclusions across studies. Most agrivoltaic literature has occurred in warm temperate climate zones and, of these, most warm temperate studies occurred in fully humid subtropical climates. As such, there is limited agrivoltaic research in climates like Washington's for comparison. From the literature compiled by Pandey et al. (2025), we extracted the literature relevant to Washington's climate regions. Of the nine warm summer Mediterranean (Csb) studies relevant to western Washington's climate, only five included actual field research on agriculture and solar photovoltaic systems. These were tomatoes in the Willamette Valley (Al-Agele et al. 2021), pasture and sheep in the Willamette Valley (Adeh et al. 2018, Andrew et al. 2021), cauliflower in Chile (Gese et al. 2019), and pasture and sheep in the Netherlands (Kampherbeek et al. 2023). There were no Arid Cold Desert (Bwk) or Cool Climate with Dry, Warm Summer (Dsb) agrivoltaic studies that involved field research on crops or livestock. Of the seven Arid Cold Steppe (Bsk) studies relevant to eastern Washington, only three used field studies with crops and solar arrays. These included work on managed grassland in Colorado (Kannenberg et al. 2023), lettuce in Spain (Carreno-Ortega et al. 2021), and aloe vera in Spain (Hernandez et al. 2022). We explore the relevant livestock literature further below but, in general, the limited research on crops grown under agrivoltaics in climates like Washington are reflective of the broad conclusions from prior reviews (Laub et al. 2022, Widmer et al. 2024). With respect to plant crops, Pandey et al. (2025) found that production tends to be greatest between solar array rows or in open fields compared to directly beneath panels, although this is dependent on the crop and climate with some crops showing similar or greater yields under panels (Pandey et al. 2025). When water (from irrigation or rain) is not limited, crop reductions tend to be higher in agrivoltaic systems but, with dry conditions including drought, crop yields could be higher under agrivoltaic systems. Agrivoltaic benefits to crop production are therefore likely highest in hot, arid climates. In non-irrigated farms in central and eastern Washington as well in western Washington with warm and dry summers, agrivoltaics may prove valuable. However, it remains unclear to what extent agrivoltaics will benefit various crops with irrigation on the Columbia Plateau, although crop quality may benefit due to reduced sunburn and other quality impacts.

Fruit crops – particularly perennial fruits – have emerged as a salient target for agrivoltaics recently. Magarelli et al. (2024) provided a targeted review on agrivoltaics focused on fruit species, particularly perennial fruit crops. Fruit may be particularly amendable to agrivoltaics as the photovoltaic system can fully or partially replace the covering and netting structures that are frequently used to protect fruit from various hazards like heavy rainfall, sunburn, hail, and heat. However, unlike standard treatments like netting, an agrivoltaic system is largely in place throughout the full agricultural cycle. This may lead to cost savings (e.g., not having to install and dismantle the shade cover each season) but also means that covering is provided continuously rather than only during the stressful period and thus may influence plant growth, phenology, etc. With respect to shading, fruit crops have been less well-studied compared to arable or horticultural crops but, in general, shading kept at ~30% or less causes yield reductions that are still marketable (Magarelli et al. 2024). At the time of publication, the body of research suggested that apples and pears show modest yield reductions but similar or tolerable quality with shading, grapes were minimally impacted by shade, and kiwifruit and cranberries were substantially impaired by shade. A similar review focused on the favorability of berry crops under agrivoltaic systems (Hermelink et al. 2024). This analysis reviewed shade research for blackberries, blueberries, strawberries, and black currants that might be relevant to agrivoltaics, although they found little direct research on agrivoltaics and berries, instead relying on shade structure experiments

(Hermelink et al. 2024). Their statistical analysis found that most berries tolerate low to moderate (up to 40-50%) shade without yield reductions whereas blueberries and blackberries actually have higher yields at 30-40% shade, particularly in regions with generally higher levels solar radiation (Hermelink et al. 2024). Hermelink et al. (2024) concluded that berries are likely a potentially suitable group of fruit for agrivoltaics given their shade tolerance and potential shade benefits to yield for some species. The scientific discourse is coalescing around fruit – particularly tree fruit and berries – as highly amenable crops for agrivoltaics, especially under extreme environmental conditions like high heat, drought, hail, etc. (Lopez et al. 2022).

Below, we provide additional detail about the scientific research on agricultural production under agrivoltaic systems that may be pertinent to Washington state. Because results on vegetable crops are highly variable, we demonstrate why drawing generalizations for such crops is challenging by pointing to evidence from multiple studies with diverse outcomes. Given the weight of science suggests that perennial fruit crops and livestock are most likely to function well under agrivoltaics, we offer additional literature review for tree fruit, berries, grapes, and livestock agrivoltaics. We emphasize research from climate zones relevant to Washington when possible but include some research outside of those climate zones if the science is focused on the agricultural types that are particularly relevant to Washington (i.e., tree fruit).

Vegetables

Little work has studied vegetable crops in climates relevant to Washington, however there is a robust literature on these crops in other climate classes. Prior literature reviews have concluded that outcomes for vegetable crops differ markedly among crop types and varieties of a given crop (Laub et al. 2022, Widmer et al. 2024, Pandey et al. 2025). For instance, summer squashes grown under agrivoltaic systems of different shading levels and configurations in Colorado and Belgium tend to decrease yield substantially by ~20-50% whereas beans grown under different agrivoltaic configurations in Belgium or Tanzania and Kenya could produce yields that are equal to or up to two times higher than beans grown without solar panel shading (Hickey et al. 2024, Nikiema 2023, Randle-Boggis et al. 2025). A relatively large amount of work has also been conducted on cruciferous vegetables (e.g., broccoli, cabbage, kale, mustard, turnips) in diverse parts of the world. This body of work suggests that crucifers can produce variable yields (lower, equal, or higher) depending on the study, but that crucifer crop quality can produce similar – and perhaps greater – marketable coloration under agrivoltaic systems as compared to standard production (Chae et al. 2022, Ko et al. 2023, Moon and Ku 2023, Oleskewicz 2020, Randle-Boggis et al. 2025, Setyorini et al. 2024). When grown under agrivoltaics, crucifers like broccoli may invest more growth into vegetative structures in response to shade stress, rather than the flowering parts that people consume (Oleskewicz 2020). Further, some research that found no impacts to kale yield under agrivoltaics also underscores how agrivoltaics can produce relatively consistent yields across seasons compared to unshaded conditions, underscoring how one benefit of agrivoltaics may be a greater predictability of crop production across seasons (Quarshie 2023).

Leafy greens like lettuce also have variable results across geographies and agrivoltaic designs. Lettuce grown under solar panels of different transparencies (0%, 5%, and 40%) in Fort Collins, Colorado tended to have higher yields than unshaded lettuce, although these differences were not statistically different (Hickey et al. 2024). Pioneering research in France grew lettuce under agrivoltaic systems that had panels in different densities (Marrou et al. 2013). This work found that full density agrivoltaic arrays that only provided lettuce 20-50% of solar radiation reduced lettuce yields to 60% of full sun conditions, but a half-density agrivoltaic system that provided 66-75% of normal solar radiation allowed lettuce yields that were 80-90% of the yields lettuce produced in unshaded conditions (Marrou et al. 2013). Additional French research on romaine lettuce grown under three different agrivoltaic systems (fixed arrays, controlled tracking, and solar tracking) all reduced lettuce yield to 75% of control conditions and halved the fraction of marketable lettuce, although the agrivoltaic lettuce increased water use efficiency (Elamri et al. 2018). An experiment in Spain similarly found that a standard agrivoltaic setup reduced lettuce yields, but that lettuce yields can be increased by 45-70%

compared to unshaded conditions by repositioning solar panels in a pattern than scatters the shadow (Carreno-Ortega et al. 2021). Belgian research grew lettuce on the east and west side of vertical bifacial panels, horizontal panels, and tracking panels found, finding that lettuce yields could be higher, equal, or reduced compared to unshaded conditions depending on the agrivoltaic design and which side of the panel the plants were on (Nikiema 2023). And work on lettuce in eastern China found that conventional agrivoltaics reduced lettuce yield by ~50% (Zheng et al. 2021). With respect to other leafy greens, agrivoltaic spinach in Japan and Swiss chard in Massachusetts showed substantial yield reductions compared to unshaded conditions (Kirimura et al. 2022, Oleskewicz 2020) whereas agrivoltaic Swiss chard doubled in yield when grown both between and under panels in Tanzania and Kenya (Randle-Boggis et al. 2025). Overall, the effects of agrivoltaics on leafy greens are variable and additional research is needed to clarify under what conditions agrivoltaics can consistently sustain leafy green production.

Finally, night shades like tomatoes, peppers, and eggplants have received substantial research attention, but also demonstrate a high degree of variability in results across studies. A rooftop agrivoltaic system in Colorado found reductions (~ 2-60% reduction) in three pepper varieties grown under opaque and bifacial solar panels, although there was no effect of panel shading on perceived flavor quality of the peppers (Gross et al. 2024). In contrast, bell peppers and jalapenos grown under solar panels of varying transparencies (0%, 5%, and 40%) in Fort Collins, Colorado produced identical yields to field-grown peppers, regardless of the transparency level (Hickey et al. 2024). An experiment that leveraged an existing solar array in a semi-arid region of Spain found that planting peppers in the corridors between solar panel rows resulted in a 60% increase in yield and fruit count compared to unshaded control conditions (Hernandes et al. 2022). Finally, agrivoltaic bell peppers in Massachusetts showed a 70-80% decrease in fruit count and weight compared to unshaded conditions (Oleskewicz 2020) and an agrivoltaic experiment in Tanzania and Kenya resulted in a ~33% decrease in sweet pepper and 50% decrease in eggplant yields (Randle-Boggis et al. 2025)

Tomatoes grown under solar panels of varying transparencies (0%, 5%, and 40%) in Fort Collins, Colorado produced identical yields to field-grown tomatoes, regardless of the transparency level, although yields were trending higher under panels (Hickey et al. 2024). Two agrivoltaic experiments in Italy – one testing conventional panels versus semi-transparent panels and the other testing different irrigation levels under agrivoltaics – found complex results with respect to shading and water efficiency on tomato yields and quality (sugar content, firmness, color, acidity, etc.) (Mohammedi et al. 2023, Scarano et al. 2024). And research in Corvallis, Oregon tested agrivoltaic tomato production under full or deficit irrigation, showing that tomatoes grown under or between solar panel rows reduced yields to 25-50% of standard full sun yields, but that water productivity (crop yield per volume of water used) was much more efficient for agrivoltaic tomatoes (Al-agele 2020, Al-agele et al. 2021).

Although the high degree of variation in results among vegetable crops impedes generalized conclusions, there are sufficient positive results to encourage further research that studies under what conditions these crops might be successful for agrivoltaics. Further, small agricultural producers interested in solar energy may still attempt to implement agrivoltaics and try various vegetable crops to see which might be productive in their property's context.

Fruit

Fruit production is a defining feature of Washington's agricultural landscape (USDA 2024). In Washington, tree fruit alone was valued at ~$2.5 billion in 2024 with apples representing nearly $2 billion of that. Raspberries, blueberries, and grapes together were valued at over $500 million. Scientific research suggests that such fruit crops may be particularly amenable for agrivoltaics (Lopez et al. 2022, Hermelink et al. 2024, Magarelli et al. 2024). Below we review targeted shade literature for some fruit crop types as well as the limited but growing agrivoltaic research for these crops.

Apples

In Washington, apple production is not only a robust economic industry but one that continues to grow in acreage (Appendix Figure 2). In central and eastern Washington, shading is increasingly necessary to protect apples from sunburn and heat stress (Mupambi et al. 2018). We reviewed roughly 30 studies assessing the effect of general shading on apples. The most common form of shading is through a black shading/ hail-net (providing roughly 20% shading) installed above the tree canopy (Mupambi et al. 2018). Although black is the most common shade netting, there are other colors of netting like white, red, and blue that provide different degrees of shading. From the body of shading research, 20-50% shading can have neutral or even positive effects on apple yield and quality, although shade effects differ between varieties of apples as some are expected to have different blush (coloration) than others. Higher levels of shading have found detrimental effects on apple tree growth and production (Miller et al. 2015, Boini et al. 2022). Positive effects of shading include higher yield in Granny Smith Challenger (Ozturk et al., 2022), decreased incidence of sunburn in Gala (Amarante et al., 2011), improved water retention in Gala Buckeye (Boini et al., 2023), and more balanced nutrition levels within Granny Smith (Ucgun et al. 2022). Negative effects of shading include delayed harvest times in Granny Smith (Ucgun et al. 2022), reduced yields in Mondial Gala (Iglesias and Alegre 2006), lower fruit weight in Ginger Gold (Miller et al. 2015), reduced firmness in Cripps Pink (Gindaba and Wand 2005), and decreased blushing or coloration in Cameron Select Honeycrisp (Serra et al., 2020). Most of these studies occurred in Europe, although multiple studies have occurred with Granny Smith and various Honeycrisp varieties in Washington orchards, typically with positive results of shading (Serra et al., 2020; Mupambi et al., 2018; Kalcsits et al., 2016; Kalcsits et al., 2017).

Beyond reviewing general shade research, we also reviewed the growing science on apples and agrivoltaics (Figure 2). A three-year study in southeastern France deployed a 16.4 ft tall agrivoltaic system over a 10-year old Golden Delicious apple orchard. The solar arrays resulted in 4-88% of incident light hitting trees under the panels (with a mean shading intensity 40-50%) and generally cooler and more humid conditions under the panels (e.g., July temperatures were cooler and relative humidity was higher under panels) (Juillion et al. 2022). Solar arrays also resulted in trees requiring 6-31% of the irrigation applied to unshaded trees. This experiment found no effect of panel shading on apple phenology (e.g., when leaves burst or flowering begins). However, shading blunted the degree of alternate bearing behavior in apple trees where some trees normally bear fruit in some but not other years. Shaded trees tended to have a lower flower density but a higher proportion of fruit remaining on the tree (due to frost protection) and tended not to decrease fresh mass but consistently decreased dry mass of fruit. At the orchard scale, there was significant inter-annual differences in yield. Specifically, in two of the three years, shading reduced orchard-scale yield by ~30% but, in the third year shading increased orchard-scale yield by 90%. Further, this third year had the lowest overall yields which, in tandem with reductions in alternate-bearing behavior, suggests that agrivoltaic shading may buffer extreme inter-annual fluctuations in apple yield, although overall yield may be somewhat reduced. This study concluded that although the agrivoltaic systems resulted in modest yield reductions, there were notable system-wide positive changes including ~ 800mm of irrigation saved over the three years, cooling benefits in summer and potential freeze protection in cooler seasons and reduced thinning costs (Juillion et al. 2022).

Researchers at the same French Golden Delicious apple agrivoltaic station recognized that fruit quality in agrivoltaic systems was minimally studied but that shading could influence the quality – and therefore the marketability – of fruit. They hypothesized that climate change could reduce apple quality (by decreasing acidity and firmness) and increase sunburn but that agrivoltaics could minimize those impacts. (Juillion et al. 2023, 2024a). With a three-year study of this apple agrivoltaic system, these researchers found no effect of agrivoltaic shading on apple firmness but did find that the fluctuating shading from the panels resulted in "greener" colored apples. Dry matter content and soluble sugars were reduced by ~15-25% and ~12-20%, respectively. Malic acid was inconsistently different (higher, lower, no difference) among years. No effect was found on bloom time, despite the measured changes in sunlight and microclimate (reported in Juillion et al. 2022). Regardless of some changes in apple quality from shading, the agrivoltaic Golden Delicious apples met the minimum marketable standards.

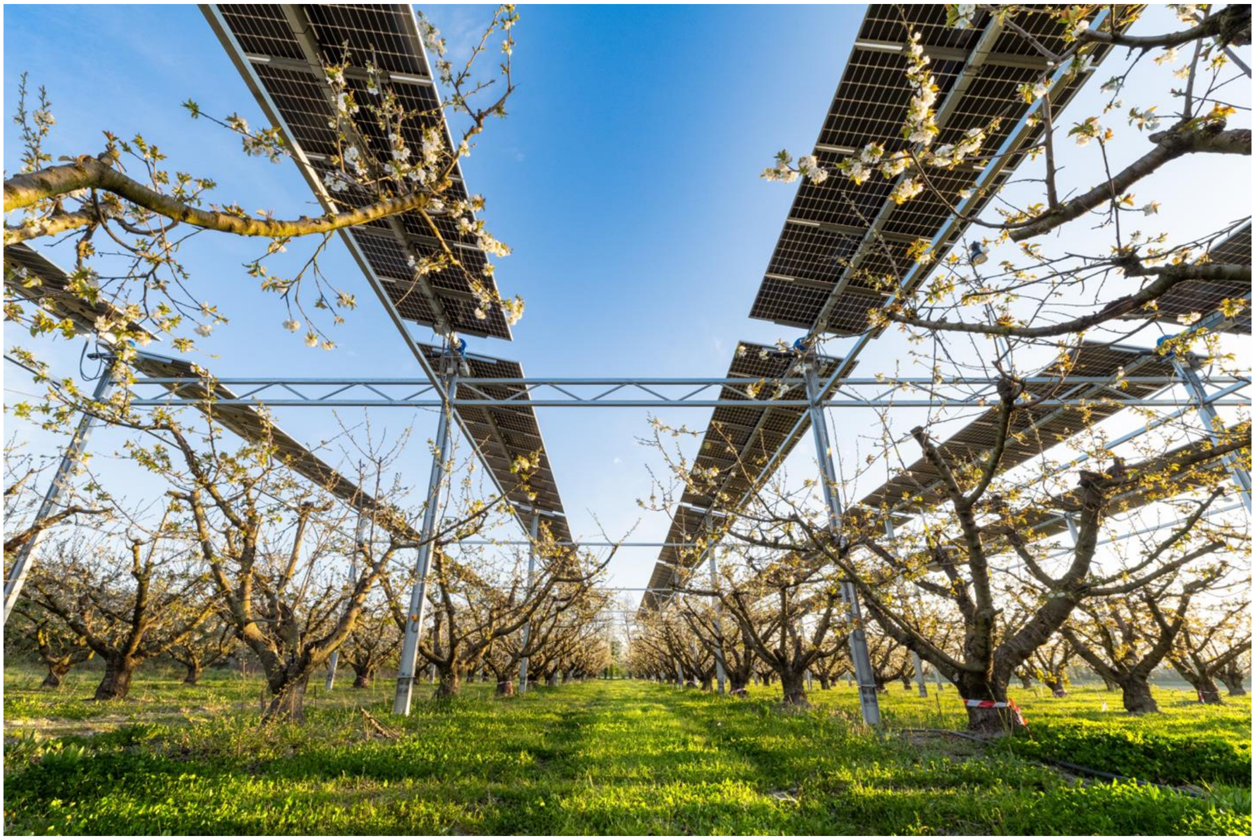


Figure 2. An apple agrivoltaic system in Europe. Image courtesy of Sun'Agri Drôme 6894.

Additional work in the French Golden Delicious agrivoltaic system found that shading from solar panels increased leaf size by ~20% and reduced net photosynthesis (Juillion et al. 2024b). This means apple trees may have a reduced ability to assimilate sugars into fruit when under solar panels. The authors suggest that minimizing solar panel shading during leaf development – rather than throughout the whole season – might minimize this problem, increasing shading on the trees once most of the leaves are fully developed. Indeed, emerging modeling work is assessing how to balance the highest potential energy production and light penetration needs for apple trees that varies seasonally depending on the needs of trees versus societal energy demand (Bruno 2023).

A non-peer reviewed preprint presents data on Gala apples grown under semi-transparent solar arrays in southwestern Germany (Velez et al. 2025). Agrivoltaic apples were consistently smaller than control apples throughout fruit development across three summer months. By September, the average agrivoltaic apple was 15% lighter and 8% narrower than the control apples. Agrivoltaic apples were also delayed in maturation by 10-12 days throughout the growing season. Because apple crops do not mature synchronously, Velez et al. (2025) were able to track changes in the percentage of the crop that was mature over the season, showing that the agrivoltaic apples were consistently lagging in maturation; by September the control group was 70%

mature but only 40% of the agrivoltaic apples were mature. Although apple sizes and thus yield were lower, the yield was still marketable, and the researchers note that the yield reductions might stabilize production of the crop over time. They also speculated that agrivoltaics would be especially useful in warmer climates.

Given the general scientific understanding of the effects of shading on apples and the existing research on apples and agrivoltaics elsewhere in the world, apples may be particularly suitable for agrivoltaics, retaining sufficient yields and quality for marketability. Notably, however, the existing research to date on apple agrivoltaics has occurred in France and Germany where climates are different than Washington's apple growing regions. It is possible that apple agrivoltaics may be more suitable in central and eastern Washington given the degree of sunburn and heat stress.

Pears

Pears remain an important component of Washington's agricultural economy, although the amount of land in pear production and the number of pear farms has continuously declined over the past 20 years (Appendix Figure 2). As with apples, we also reviewed literature around shading and pears. Research on pears and shading is more limited than the research on apples, however 24-40% shading appears to offer neutral to positive effects, depending on the time of day that shading is applied and the duration of shading after bloom. Much like with apples, the primary form of shading for pears is shade netting (anywhere from 20-80%) installed above a tree's canopy. Positive effects of shading include decreased russet (skin blemishing) in Spadona (Shahak et al., 2006), high blushing coverage in Rico with shorter shading periods after full bloom (Peavey et al., 2020), increased yield in Nijisseiki (Feng et al., 2018), protection from extreme weather events in Korla (Wang et al., 2022), decreased excessive growth in Nijisseiki (Feng et al., 2018), and maintained quality in Conference (Reher et al., 2025). Negative effects included firmer flesh in Bartlett (Garriz et al., 1997), reduced fruit mass and diameter in Bartlett (Garriz et al., 1998), and loss of blushing in Lanya (Peavey et al., 2022). Most pear shading research occurred in Australia and Argentina and, to our knowledge, none occurred in Washington State. Further, research on Asian pear varieties may not be relevant to Washington which tends to produce European varieties.

Like apples, there is a limited but growing body of research on pears and agrivoltaics (Figure 3). Preliminary results from a mature orchard in Italy that was retrofitted as an agrivoltaic system with semitransparent photovoltaic modules producing a ~30% light reduction show that pears experienced a 16% reduction in yield both by a reduction in fruit count and size (Reher et al. 2021). Interestingly, this yield wasn't symmetrical. The orchard orientation results in the east side of the trees receiving more sunlight and therefore a higher pear yield in the control, unshaded trees. In contrast, pear production on the west versus east side of the trees was equivalent in the agrivoltaic trees and similar to the west-facing or less sunny side of the control trees. Thus, agrivoltaics provides a more even fruit count within individuals compared to unshaded orchard trees. Despite the yield reduction, fruit quality before and after cold storage was identical between agrivoltaic and unshaded pears (Reher et al. 2021).

In Belgium, a pear agrivoltaic system replaced a hail net, trellised system and researchers found that the system reduced yield by 16% (Willockx et al. 2024). Fruit yield reduced as both a function of fruit number and smaller fruit size, although pear quality (firmness, brix, color, ethylene production) was identical under the agrivoltaic system as compared to standard conditions. The researchers underscored how larger agrivoltaic systems with orchards are likely more economically viable due to the economies of scale, perhaps suggesting the potential for utility-scale agrivoltaic systems. The same Belgian pear agrivoltaic system (11 ft inter-row spacing, 14 ft high semi-transparent panels) found that the agrivoltaic systems had generally similar temperature patterns as control conditions (Reher et al. 2025). However, in early spring nights the agrivoltaic system was ~0.5 C warmer, providing some frost protection. During the daytime, the agrivoltaic system was ~0.35 C cooler than the control system. On hotter summer days, the canopy temperature under the agrivoltaic system was similar to control conditions. The agrivoltaic system had no effect on flowering or fruit drop behavior on the trees, however, the agrivoltaic systems reduced fruit yield by 15%, although the reduction was not significant due to the high variability in the agrivoltaic replicates. Fruit size (weight and diameter) and count were largely not impacted by the agrivoltaic systems either. Agrivoltaic pears tended to produce more – but not substantially more – bottle shaped fruit which could reduce marketability. The ethylene production (which influences ripening post-harvest) was similar between agrivoltaic and standard pears. Fruit quality measured by brix, reactive starch index, and firmness were all largely identical between agrivoltaic and control pears. In sum, Belgian research suggests that pear trees can retain sufficient yield and marketable quality under agrivoltaics.

Figure 3. A pear agrivoltaic system in Europe. Image courtesy of Thomas Reher.

Work in southern Australia studied trellised pears under a fixed-tilt agrivoltaic system of two angle treatments (45 or 5 degrees) (Singh et al. 2023). Both agrivoltaic treatments reduced fruit diameter by ~4-7% at harvest with the larger fruit under the 5-degree tilt compared to the 45-degree tilt. A quantitative color index showed that the agrivoltaic system produced a 20% reduction in redness compared to control condition. Agrivoltaic trees under 5-degree tilt produced roughly 50% as many fruits as the control trees, and trees under 45-degree tilt produced statistically similar numbers of fruits as control trees although with a trend towards fewer fruit. Agrivoltaic trees panels produced fruit with a ~8-10% reduction in weight. Overall yield from agrivoltaic trees was ~50-66% of control trees. Control trees had ~13% higher brix, similar firmness, and redder or more blushed quality compared to agrivoltaic pears. However, agrivoltaics yielded a 95% reduction in sunburned fruit, although only 3.4% of control fruit were sunburned. The authors note that there were few extreme heat days over the course of this study, thus agrivoltaics may provide more protection in hotter years. It is unclear whether the agrivoltaic effects here sufficiently impaired marketability, although this research from Australia suggests poorer performance of pears under agrivoltaics. A report from Korea studied a folding agrivoltaic design over pear orchards, finding that the solar panels extended the flower period by five days and decreased fruit drop by 38% under a typhoon (Gim et al. 2020). Agrivoltaic pears decreased yield by ~7%, fruit sized dropped by 4.5%, and there was a 1.3 degree drop. Although data on Asian pears likely do not translate well to Washington agricultural context, conclusions from this Korean research largely mirror pear agrivoltaic research in Europe. Overall, emerging research suggests that pears may be amenable to agrivoltaics but that there may be variability among varieties and climates that impact success. As with apples, little of this research occurred in climates that are directly comparable to growing conditions in Washington's pear growing regions.

Other Tree Fruit

Cherries are another important tree fruit in Washington that continue to increase in acreage despite a decline in the total number of cherry farms in the state (Appendix Figure 2). To our knowledge, there is no research or ongoing demonstration project on agrivoltaics and cherries. Although there is little research on agrivoltaics and cherries, our review found nine studies on cherries and shading in general. The most common form of shading for cherries is netting (roughly 30% on average), with research suggesting that 20-40% shading has neutral or sometimes positive effects. Positive results include increased yield in Samba, Rita and Bellise (Overbeck et al. 2018), improved water use efficiency in Sweet Cherry (Centritto et al. 2000), reduced fruit cracking rates in the Chinese Cherry (Tian et al. 2019), and increased fruit weight in Lapins (Schettini et al. 2010). Negative effects include poorer coloration in Hong Deng (Tang et al., 2023), lower soluble solids in Bing (Patten and Proebsting, 1986), and reduced weight and overall quality in Hong Deng (Tang et al., 2023). Only one of these studies was done in Washington State at the WSU extension in Prosser (Patten and Proebsting 1986). Given the neutral or positive effects of shading on cherries, this crop type may be worth exploring under agrivoltaics in Washington state.

Little research has occurred on agrivoltaics and other tree fruits. There is one study on mature nectarine trees in France that placed an agrivoltaic system over the orchard and rotated the panels horizontally at night to create a thermal buffer that protected flowers during freezing temperatures. This work found that the panels maintained flower buds up to 1-2 C warmer during cold nights, reducing frost damage to flowers from 35% in control conditions to less than 10% under solar panels (Lopez et al. 2023). There were few inferences about fruit yield or quality, although frost protection was substantial. And there is active research in France about whether dynamic agrivoltaics (altering panel angle depending on the plant's seasonal needs) can mediate both cold- and heat-related climatic events on apricots (Jardon et al. 2024). Apricots and nectarines represent relatively small – and declining – acreage in Washington (Appendix Figure 2) but still may be worth exploring as potential agrivoltaic crops.

Grapes

Vineyards are an important part of Washington's agricultural landscape, particularly due to a robust and increasing wine industry. A small but growing scientific literature now exists for both wine grape and table grape agrivoltaics (Figure 4). An agrivoltaic experiment on Primitivo (zinfandel) wine grapes in the southeastern Italian region of Puglia used fixed tilt panels that exposed half of the vine canopy to low light throughout the day found that shading from solar panels increased grape yield by >270% and increased bud fruitfulness compared to unshaded conditions (Magarelli et al. 2025). Both lower shade areas (5% shade) and higher shade (95%) shade areas beneath the panel increased soil moisture and decreased soil temperatures, although temperature effects were less pronounced. The higher shaded parts of the array also reduced median daily mean air temperatures by roughly 1 C. A four-year study in the south of France on grenache blanc wine grapes deployed a dynamic agrivoltaic system that was controlled with artificial intelligence. This agrivoltaic system altered the amount of shading throughout the season depending on what the vines required during different parts of its phenological cycle (Fumey et al. 2023). When the solar panels were programmed to track the sun, they reduced temperatures by 2 C and when they were set to not track the sun (i.e., fixed), they reduced temperatures on average 0.5 C. The altered environment from the panels improved water use by the vines, resulting in a 37-62% reduction in irrigation needed (depending on the season). The final year of the study included an abnormally hot summer; whereas control vines showed visual symptoms of heat stress (leaf damage and fruit sunburn), the agrivoltaic vines did not.

Figure 4. A grape agrivoltaic system in Europe. Image courtesy of Sun'Agri Tresserre.

Although a markedly different climate than found in Washington, there is some research on agrivoltaic table grapes in Korea. A study in coastal west South Korea compared table grape production under an agrivoltaic system comprised of standard panels, bifacial panels, and transparent panels (Cho et al. 2020). Transparent panels produced the most grape granules followed by bifacial and then standard panels, but all panels produced lighter granules compared to unshaded conditions. Brix (sugar content) was highest in unshaded conditions, lowest under transparent panels, and intermediate under the other panels (Cho et al. 2020). The panels functionally reduced the maturation of the grapes, but the researchers found that delaying harvest under panels by 10 days allowed them to produce marketable fruit that was comparable to grapes grown under control conditions. Another agrivoltaic table grape experiment in Korea found no influence of solar panel shading on fruit production (cluster weight, length, diameter, and berry weight) or vegetative growth (i.e., budding date, number of shoots per vine, shoot length, number of leaves per shoot, internode length and diameter, leaf weight, or leaf area). Harvest timing was somewhat delayed 7-10 days under solar panels (Ahn et al. 2022). Ahn et al. (2022) also found that the solar panels acted as a wind break for the vines, particularly in winter, and reduced soil temperatures. At least in the humid subtropical/continental climates of South Korea, table grapes appear to function well in agrivoltaics.

Overall, both wine grapes in Mediterranean climates in Italy and France and table grapes in humid subtropical/continental climates in South Korea function well in agrivoltaic systems. A limitation to grape agrivoltaics in Washington is the row-straddling mechanization typically used for harvest that may impede solar arrays (personal communication with Freddy Arredondo).

Berries

Berries remain an economically important part of Washington's agricultural landscape and blackberries, blueberries, and raspberries have largely increased in acreage over the past ~30-50 years, although strawberries have declined markedly in acreage (Appendix Figure 3). There is little published research directly testing berries under agrivoltaic systems, although scientists assume that berries should do well given the high degree of shade tolerance – and even shade benefits – of various berry crops when studied under shade cloth structures (Hermelink et al. 2024). Raspberry and blueberry agrivoltaics are underway in Lisbon (Hauser 2023), although no work has been completed yet. A preliminary report from the Netherlands compared raspberries in an agrivoltaic system to a standard raspberry system covered with plastic covering and shade netting (Helsen et al. 2022). The agrivoltaic system resulted in 42% lighting whereas the standard system resulted in 58% of full light. The agrivoltaic system led to a 35% increase in total leaf area, a 5% reduction in fruit yield, and fruit that were 1.5 Brix lower. Even so, the authors concluded that the commercial quality was satisfactory. In the Netherlands, a preliminary report compared strawberries grown under solar panels to those grown in open conditions, finding that total leaf area decreased ~20-40% and fruit production decreased ~25-40% (Helsen et al. 2022). A recent experiment tested different solar panel transparency levels from 10-80% transparency on strawberry growth (Jamil and Pearce 2025). 70% transparency (i.e., higher light penetration to the plants) provided greater strawberry yield than unshaded control conditions. ~40% and higher transparency provided strawberry yield that was ~80% of control conditions, potentially sufficient for marketability. The higher transparency levels only delayed fruiting time by roughly 1 week whereas the lower transparency delayed by ~40 days. This experiment was in a controlled greenhouse environment and so it is unclear how various panel transparencies would function – both for energy and strawberry production – under field conditions. An experimental plywood 'agrivoltaic' system deployed over a cranberry bog in Massachusetts reduced cranberry yield by almost half and reduced berry firmness and weight by ~10% (Mupambi et al. 2021). This work suggests cranberries are likely unsuitable for agrivoltaics, although this research happened in a different climate than western Washington'.

Although berries hypothetically should function well under agrivoltaics, little research is published on berries in agrivoltaic systems. The scant research available occurred in climates that are dissimilar to Washington and so additional work is needed to understand the potential for berry agrivoltaics in the state. Similar to grapes, much of Washington's berries are harvested with row-straddling machines that might constrain agrivoltaics (personal communication with Mia Devine, Chris Henderson, and Freddy Arredondo).

Herbs and Medicinal Plants

Herbs have received comparatively little attention in agrivoltaic research. Even so, some emerging research suggests these crops may be particularly amenable to agrivoltaics. For instance, Disciglio et al. (2023) suggested that, because shading often encourages plants to invest more in vegetative growth – especially in arid and/or hot environments – that agrivoltaics could be particularly amenable to crops like herbs or medicinal plants, where leaves and stems are primarily harvested. In southern Italy, researchers studied sage, oregano, rosemary, lavender, thyme, and mint. Sage grown under solar panels were 40-60% larger than under control conditions; because this was a one-year study, no size data were provided for other crops (Disciglio et al. 2023). Sage, mint, lavender, and rosemary had 10-15% higher essential oil production with similar – but nonsignificant trend seen in oregano and thyme. Research in Spain found a 20% increase in thyme yield and 30% increase in aloe leaf yield when planted when planted in the corridors between solar panel rows at an existing utility-scale solar array (Hernandes et al. 2022). An agrivoltaic experiment in Tanzania and Kenya found a coriander yields were 10% higher under solar panels than in unshaded conditions (Randle-Boggis et al. 2025). Although leafy herbs appear to do well, work on herb roots like ginger and garlic suggest substantial yield reductions, although research is limited on these crops (Ko et al. 2023, Quarshie 2023).

Finally, a pilot hop agrivoltaic project in France grew hop vines up a 23 ft solar panel structure, showing that agrivoltaic hop yields are 70% of hops grown in full sun (Folton 2023). Even so, the agrivoltaic system also reduced mildew pressure, decreasing the number of mildew impacted plants from 80% under unshaded conditions to 55% for the agrivoltaic hop plants. Aphids tended to be more pronounced under the solar panels. Given hops comprised >30,000 acres in Washington and were valued at > $300 million in 2024 (USDA 2024), further exploration of hops and agrivoltaics in the state may be worthwhile. Further, other herb crops like lavender and mint may also provide agrivoltaic opportunities in Washington.

Livestock

Figure 5. Sheep grazing at the Goose Prairie solar farm in Moxee, WA. This is likely the first agrivoltaic project in Washington state. Picture courtesy of Brookfield Renewable

Photovoltaic arrays require vegetation control to maintain safety and operations. Livestock agrivoltaics (i.e., solar grazing) has emerged as an innovative option for solar array vegetation maintenance as the vegetation control provided by grazing livestock sustains the livestock production itself. Sheep are considered well-suited for agrivoltaics (Figure 5) because their smaller size means panels do not need to be racked particularly high and, compared to goats, sheep will not tend to jump on panels or chew on wires (Vaughan and Brent 2024). Although livestock agrivoltaics has been a growing practice, research in this area is still in its infancy. Even as recently as 2021, there were no published studies on the efficacy of livestock agrivoltaic systems (Andrew 2021a). There has been limited discussion about agrivoltaics and smaller livestock like poultry or rabbits (Lytle et al. 2021, Pascaris et al. 2021, Carrausse and de Sartre 2023), however most research has centered on larger mammals, particularly sheep.

A recent analysis by Vaughan and Brent (2024) found minimal research on agrivoltaics and small ruminants, although there was growing interest given that heat stress can reduce sheep growth, production, milk yield, and reproduction particularly with climate change. Sheep are often considered for solar grazing endeavors as an alternative form of necessary vegetation maintenance to save on costs or impacts from mowing or herbicide use (Vaughan and Brent 2024). A recent review of 'solar grazing' using sheep highlights the widespread adoption of this approach by utility-scale solar operators as a way for sustainable and economically managing vegetation, minimizing fire risk, and allowing photovoltaic arrays to operate efficiently without being shaded by tall vegetation (Stewart et al. 2025). A challenge across the U.S. is that sheep farming has declined substantially in recent decades (this is true in Washington; Appendix Figure 4), meaning farmers are having to grow their flocks in order to meet demand by utility-scale solar developers. Stewart et al. (2025) note the conundrum that shading by panels can reduce the forage amount and quality needed to sustain sheep on-site. Rotationally grazing sheep under utility-scale solar arrays has as emerged as a growing interest because sheep can control vegetation more affordably and efficiently than mowing and string-trimming that is required to minimize shade onto panels and fire risk, and because sheep can provide an agricultural product (e.g., meat or wool), although there are additional logistical constraints for solar developers including new fencing, water sources, and sometimes predator considerations (Kochendoerfer et al. 2019).

Research in Corvallis, Oregon found that partial shade adjacent to solar panels yielded similar pasture grass growth to unshaded areas whereas pasture growth immediately beneath panel was markedly lower than unshaded conditions or pasture between panel rows (Andrew 2020, Andrew et al. 2021a,b). Lamb behavior (foraging, idling, ruminating, etc.) was identical between agrivoltaic and open field systems. However, agrivoltaic lambs spent nearly 100% of their idling and ruminating time under the shade of the panels, suggesting a preference for shaded conditions if offered (Andrew et al. 2021a). Over a two-year period, lambs grew at equal rates when raised in agrivoltaic pastures versus open pastures. However, open pasture lambs consumed significantly more water (0.7 L/head/day) than agrivoltaics lambs in one year but showed equal water consumption in the second year. Interestingly, lambs necessarily had to be stocked at a higher density (14.8 lambs/acre vs 12.2 lambs/acre) in the agrivoltaic pasture versus open pasture. As such, this Oregon research concluded that agrivoltaic grazing has the potential to raise lambs at higher density with no impact on lamb growth and potentially reduced environmental stress on the animals.

Additional work at this Corvallis facility tested the effects of agrivoltaics on three pasture plantings: simple (five species), diverse (12 species), and legume (eight species) (Andrew et al. 2024). Overall, simple and diverse pastures grew faster in unshaded conditions and grew faster than legume fields in general, but legume fields were not affected by solar panel shading. Lambs raised on legume pastures gained weight faster, but lambs raised on diverse pastures gained a higher overall liveweight. This study also concluded that the standard ground-mounted solar array structure is not conducive to pasture production as the area beneath panels – which constituted 50% of the plot's area – had a 30% reduction in forage production. Overall, although legume pastures tolerated shade from the panels the best and produced the greatest initial lamb growth, these fields did not produce sufficient forage across the season. Diversified forages appear to have produced the most forage in an agrivoltaic system and resulted in consistent lamb growth across seasons.

At two solar sheep grazing sites in France, researchers monitored microclimate variables and forage production, finding that the cooler, moister soil under panels resulted in high vegetative growth (~150-210% of typical forage height) and that forage height growth was more stable in the agrivoltaic fields than in unshaded conditions (Loan et al. 2022). Although forage height was influenced by panels, forage biomass was similar between panel and control areas. Depending on the farm studied, inter-row vegetation either mirrored unshaded conditions (when row spacing was wider) or conditions under solar panels (with narrower row spacing). Notably the site with wider row spacing produced the highest biomass under panels, lowest between panel rows, and control biomass was intermediate. In contrast, with the narrower row spacing, the highest biomass was between panel rows, lowest under panels, and intermediate between. This highlights how site conditions and array design can influence desired forage outcomes. This work also found a generally higher quality forage under panels.

Research in Brazil is showing the value of solar panel shading for sheep welfare. One study in Brazil offered paddocked sheep shade from a shade cloth, shade from a solar array structure, or no shade, finding that sheep showed a strong preference for shading provided by solar panels rather than shade cloth (Maia et al. 2020). When under the solar panels, the sheep also spent much of their time lying down, suggesting the shade provided a comfortable and relaxing environment (Maia et al 2020). In Sao Paolo, research showed that meat sheep with agrivoltaic shading reduced their body temperatures by 0.7 C and increased the feeding efficiency (food consumed / mass gained ratio (Fidelis et al. 2023). On hotter days, sheep without access to agrivoltaic shading were not only hotter but also had a 20% higher respiration rate, demonstrating heat stress. When provided shade from solar panels on these days, sheep increased the use of that shade by 65%.

Figure 6. Cattle grazing at an experimental solar array in Minnesota. Picture courtesy of Bradley Heins.

Comparatively little research has studied the biology of cattle – dairy or beef – in agrivoltaic systems. Even so, cattle agrivoltaics are being piloted (Figure 6). For instance, New Zealand has invested in a solar farm that integrates elevated solar panels with dairy cattle grazing given the high amount of modeled agrivoltaic-suitable land in the country (Brent 2024). Some research is also emerging from Minnesota. Specifically, a short-term experiment in Minnesota on the effect of a 30 kW solar array raised 8-9 ft off the ground on organic pastured-based dairy cattle found that shading from the panels produced a 15% decrease in afternoon respiration rates and reduced afternoon body temperatures in cows while largely showing little impact on cow milk production or hygiene (Sharpe 2020, Sharpe et al. 2021, Heins et al. 2022). The authors proposed that the <1 month summer duration of this study may have limited inferences about solar production on milk production, although the potential animal welfare benefits with respect to body temperature and respiration rates were clear. Further, during a drought year, a forage study in Minnesota grew forage (alfalfa, field peas, meadow fescue, orchard grass, red clover, etc.) and three mixes beneath a 30 kW or a 50kW solar PV array, each mounted 8-10 ft off the ground to allow for cattle to graze (Porter 2023). Both agrivoltaic systems reduced total forage aboveground biomass by 50%, although forage mixture plots produced similar biomass as under control conditions. Agrivoltaic pastures also produced forages of higher quality with greater crude protein, fiber, digestibility, and mineral content. Although the research is still very limited, there is a growing implementation of cattle agrivoltaics.

Overall, research suggests that grazing solar arrays may be an ecologically and agronomically beneficial practice. A recent artificial grazing (i.e., mowing instead of livestock) experiment at Jack's Solar Garden in Colorado on grassland formerly managed for hay production found that ungrazed agrivoltaics (standard photovoltaic array spacing, elevated to facilitate potential cattle grazing) sites were similarly productive to ungrazed grasslands, but that 'grazing' solar arrays increases overall grassland productivity (Sturchio et la. 2024). The authors concluded that an agrivoltaic setup can sustain and extend the seasonality of grazing in semi-arid grasslands. Although the research focused on whether solar grazing can improve economic efficiencies or improve livestock products is limited, the body of research to-date shows that solar arrays can maintain adequate pasture for raising livestock and that livestock welfare under hot conditions is seemingly improved. In Washington, the cumulative number of cattle and sheep have declined in recent decades (Appendix Figure 4). Interestingly, farms with cattle have also declined in number while farms with sheep have oscillated upward. Goose Prairie Solar Farm in Moxee, WA recently introduced sheep grazing (Figure 5) as a cost-efficient method of vegetation control, because sheep reduce fire risk compared to mowers which could spark ignition, and because sheep fertilize the land and improve ecological conditions (personal communication from Amy Burnett at Brookfield Renewable). To our knowledge, Goose Prairie Solar Farm may represent the first agrivoltaic project in Washington. Further, the shepherd grazing Goose Prairie communicated to us that solar grazing may provide new opportunities for grazing sheep flocks in Washington as public lands are terminating domestic sheep grazing (personal communication from Nick Martinez). Public lands are increasing restricting sheep grazing due to the spread of *Mycoplasma ovipneumoniae* to native bighorn sheep (personal communication from Kyle Garrison, Washington Department of Fish and Wildlife).

Economics

The biology of crops and livestock is a critical dimension of the success of agrivoltaics. Another essential consideration is whether markets exist or could be created for agrivoltaic products and whether agrivoltaic systems are feasible. There is a burgeoning field of research that is addressing those two issues.

Willingness to Pay

An emerging body of science is assessing whether agrivoltaic products could create new market preferences. In Germany, consumer preference surveys compared 'willingness to pay' for apples produced using agrivoltaics versus standard production and compared this to consumers' willingness to pay against plastic, pesticide, and water usage, whether fruit was organic, and domestic versus imported fruit (Jurkenbeck and Schulze 2024). German consumers showed a high willingness to pay for apples grown via agrivoltaics compared to conventional methods and this was similar to their willingness to pay for domestically-grown fruit and fruit that used less plastic. Interestingly, Germans had a higher willingness to pay for agrivoltaic apples than for organic labeling or knowledge about pesticide or water usage. An experiment in Tucson, Arizona grew agrivoltaic tomatoes, basil, potatoes, red beans, and butternut squash and tested whether consumers could taste differences between these agrivoltaic crops and crops grown under standard conditions (Rogers 2022). This study found that consumers found no taste difference between agrivoltaic and standard tomatoes, basil, potatoes, or squash, although they preferred the taste of standard red beans. Regardless, consumers were over four times more likely to pay more for agrivoltaic produce than conventional produce. A non-peer reviewed preprint assessed > 1,300 Canadian's willingness to pay for agrivoltaic strawberries, testing the relative influence of climate risk and perceived 'green washing' (Ha et al. 2024). The researchers found that 40% of Canadians would pay a 5-10% premium for agrivoltaic strawberries over normal strawberries. It is noteworthy that climate risk perception was linked to an increased willingness to pay, suggesting that branding around ethical farming and food consumption could be important. Although some consumers had a degree of distrust for sustainable products, their 'green trust' was higher than their skepticism, suggesting that branding could mitigate potential impacts of the novelty of agrivoltaics on consumer wariness. Organic and locally-grown strawberries already obtain a premium from consumers and so it is plausible that agrivoltaic berries could also earn a premium. Overall, results from Germany, Arizona, and Canada suggest that the marketability of agrivoltaic crops could be an important consideration and that many consumers are willing to pay a premium for agricultural products that are produced simultaneously with renewable energy. Even so, experimental willingness to pay research will be necessary to understand the potential of creating new market preferences.

Viability

Operationally, it is valuable to distinguish small-scale agrivoltaic systems from utility-scale agrivoltaic systems. Pandey et al. (2025), like much of the literature, define utility-scale as > 1 MW, however we note that the Washington State Department of Ecology defines utility scale as at least 20 MW (~100-200 acres of standard ground-mounted solar). Small-scale agrivoltaics are likely to be invested in directly by the farmer, often to recover savings on electricity bills whereas utility-scale agrivoltaics will likely require third party investors to develop and operate the PV system in coordination with farmers and landowners (Pandey et al. 2025). Solar array investments are 1-2 orders of magnitude greater than the investments needed for agricultural production, meaning farmers will likely be unable to invest by themselves in the agrivoltaic setup, particularly for larger agrivoltaic systems. Further, capital expenditures for agrivoltaic systems relative to standard ground mounted systems can be 40-70% higher due to the additional requirements for soil protection considerations and the additional infrastructure for mounting, although these prices are likely to come down as more agrivoltaic projects are implemented (Pandey et al. 2025). We note that NREL data show that rooftop solar is consistently ≥ 2X the cost per MW compared to utility-solar (Ramasamy et al. 2023); thus, even though agrivoltaics may be more expensive than utility-scale solar, agrivoltaics are still more economically efficient than rooftop solar.

Although capital expenditures are higher, operating expenditures tend to be ~13% lower for agrivoltaics compared to ground-mounted solar arrays due to vegetation management reductions (due to livestock grazing or crop management rather than mowing) and general land maintenance and security (Pandey et al. 2025). When accounting for both capital and operating expenditures, the levelized cost of energy (LCOE; per unit cost of energy over its lifetime) for overhead agrivoltaics is 38% higher than ground-mounted solar, primarily due to the added cost up front for elevated panel mounting. LCOE will depend substantially on the solar insolation of an area, mount design, cost of land, and finance discount rate. With respect to capital expenditures, a key caveat is that farming approaches like sheep grazing or smaller diversified farms that hand harvest will tend to have similar expenditure as standard ground-mounted solar because few modifications to the solar arrays are needed to support the agriculture (Pandey et al. 2025). With respect to agricultural costs, the relative capital and operating expenditures between agrivoltaics and standard agricultural practice can be higher, similar, or lower (Pandey et al. 2025). This is hard to predict as cost differences will depend on differences in site preparation needs after solar array installation, irrigation savings from the solar array microclimate, whether the photovoltaic infrastructure can replace trellising and shade cloth, etc. Regardless, most of the revenue (75-90%) in agrivoltaics comes from energy generation, not agricultural production. Agrivoltaics can increase revenue per acre from 4-15X over typical agricultural production. We note that depending on the ownership/lease structure, solar energy revenues do not necessarily flow to agricultural producers, which may impede agrivoltaic uptake. Even so, agrivoltaics revenue generation will be lower than ground-mounted solar arrays because of the lower density of panels per acre and because panel orientation is not necessarily designed for maximal solar energy production but a balance of energy and agricultural production (Pandey et al. 2025). Agrivoltaics can be competitive or more profitable than ground-mounted solar arrays, depending on the policy incentives (Pandey et al. 2025).

Few crops appear to show increased yield and/or quality under shading produced by agrivoltaics. Most crops either are impaired too much by shading to be viable under an agrivoltaic system or they can tolerate the shading with minimal or modest yield decreases. The economic viability of any given crop under an agrivoltaic system depends on the value of the crop and the degree of yield impacts. For instance, work in Japan found that both mustard greens and turnips experienced similar, pronounced yield reductions under agrivoltaics but agrivoltaic mustard was still economically marketable when accounting for energy production and crop sales whereas turnips are not (Kirimura et al. 2022). Several studies have assessed the economic viability of agrivoltaics for crops relevant to Washington, although none of these occurred in Washington.

Apples, Grapes, and Tomatoes

A limited number of studies have rigorously assessed the economic viability of crops in an agrivoltaic system. Limited analyses have shown, for instance that the return-on-investment for 10 ft tall agrivoltaics over apple and cherry trees in India is 6-8 years in the absence of subsidies (Khera et al. 2024) or that agrivoltaic systems are economically prohibitive for blueberries in Chile compared to standard fruit protection (e.g., cloth, plastic; Jung and Salmon 2022). Modeling of table grape vineyards in India concluded that placing solar panels over vineyards could dramatically increase the profitability of farmland through energy production, however, this modeling only accounted for additional revenue due to electricity production and did not include potential impacts to grape yield (Malu et al. 2017). Several studies have holistically accounted for the tradeoffs in agrivoltaic systems and compared the economics to standard ground-mounted solar and standard agricultural practices.

A preliminary economic analysis of apple agrivoltaics in Germany suggested that, despite the capital-intensive up-front costs for agrivoltaics and modest reduction in agricultural production, agrivoltaics orchards are economically viable and create higher profits than orchards relying on netting infrastructure to protect fruit (Hopf et al. 2021). However, Trommsdorff et al. (2023) provide perhaps the most comprehensive economic analysis of agrivoltaics. This study assessed three apple orchard agrivoltaic pilot systems in Germany and accounted for multiple positive and negative synergies of an orchard agrivoltaic systems. Positive synergies include eliminating investment costs of the orchard trellis (if used) and hail/sun netting because the solar infrastructure serves the trellising and protective purposes, reduction in labor for flower and fruitlet thinning due to reduced light, a reduction in pesticide (fungicide) application due to shelter from moisture, a reduction in labor to open and close netting each season, reduction in irrigation due to cooler temperatures, reduced frequency of infrastructure replacement as netting is replaced more often than solar infrastructure, and potential reductions in land leasing if farmers split the lease of land. There are potential negative effects of the agrivoltaics system on costs, including the need for more intensive soil preparation for new plantings after solar installation which likely compacts the soil more than netting does and potentially more mites and aphids due to moderated temperature, air flow, and precipitation on the plants.

After accounting for this complexity, Trommsdorff et al. (2023) show that apple agrivoltaics in Germany are only economically possible in a regulatory context with a sufficiently high feed-in tariff or other regulatory payment system. Although the overall cost of apple production reduces by 5% in an apple agrivoltaic system, even after accounting for potential reductions in apple yield and quality, the levelized cost of energy due to the elevated panels is nearly 60% higher than a standard ground-mounted system. Trommsdorff et al. (2023) note that this increased cost of energy is still 40% more cost effective than a rooftop solar system. Because of the limited data available, this economic analysis was highly sensitive to assumptions about shading impacts to apple quality and yield as well as the feed-in-tariff rate which could make an orchard agrivoltaic project generate either a profit or a loss. A similar economic analysis for a proposed apple agrivoltaic system in Hungary – where apples have a lower net present value than in Germany – concluded that the feed-in tariff rate regulated the cost of an apple agrivoltaic system more than any other input including climate, apple yield, net investment, or inflation (Chalgynbayeva et al. 2024). Although this study showed that feed-in tariffs result in greater profitability for standard ground-mounted solar projects compared to agrivoltaics, feed-in tariff structures could be designed to subsidize agrivoltaics if the goal was to maintain agricultural production, benefit farmers with added revenue, and generally enhance land sparing for both natural and agricultural lands.

An economic analysis of agrivoltaic wine vineyards in Germany finds that agrivoltaics are not an economically viable option under current capabilities (Strub et al. 2024). This analysis compared various agrivoltaic scenarios to standard production, finding that any agrivoltaic vineyard would inherently be unprofitable with respect to the viticultural side of the operation. In the analysis, under the agrivoltaic scenario that allowed for the most wine grape yield while still allowing energy production, the solar energy side of the operation was not sufficiently profitable, causing the whole operation to be unprofitable. The modeled agrivoltaics scenarios that were profitable due to energy production required reducing grape yield by half or more, functionally eliminating the agricultural component of the operation. As with other economic models, vineyard production is never economically robust enough to outweigh the economic dimensions of energy production (Strub et al. 2024).

A analysis on agrivoltaic tomato production in Colorado studied the economic tradeoffs of solar and/or tomato production by accounting for the impacts of how much sunlight is allocated to the crop versus energy production (i.e., due to panel spacing, panel transparency levels, etc.) and varying degrees of agrivoltaic coproduction (versus standard tomato production or solar energy generation) on a given parcel (Buzzelli 2024). In Colorado, tomato plants have higher yields under solar panels (regardless of panel transparency), but agrivoltaic systems tend to reduce tomato yield due to the lower density of plants per acre. This analysis found that splitting a field between half tomato production and half solar energy production – without agrivoltaics – results in a halving of the crop production but a net revenue that is 2.5 times what a grower would earn from just farming. A scenario that produces no crops and maximizes solar energy production results in a revenue that is four times what farming generates. Intermediate scenarios that generate relatively small amounts of energy using 40% transparent panels produce relatively high crop yields, but with net revenues that are lower than if the farmer had maximized crop production, resulting in relatively small energy production, reduced crop yield, and reduced revenue. Co-production scenarios with 5% transparent panels and with most land in agrivoltaic production (rather than splitting solar and crop production within a field) produce the highest revenues across scenarios that incorporated agrivoltaics. The highest agrivoltaic scenario resulted in a net revenue that was three times that of a crop-only scenario and also resulted in substantial energy and tomato production. Importantly, the most profitable agrivoltaic scenarios will always result in some reduction in crop production; energy production alone will always be more profitable than agriculture or agrivoltaics, but more inefficient with respect to land use and results in a loss of food production. The researchers noted that the USDA's REAP (Renewable Energy for America Program) loans (up to 75% of project costs) and grants (up to 50% of project costs up to $1M) would help with agrivoltaic costs but would be insufficient to justify even the most profitable agrivoltaic project in Colorado tomatoes compared to a project that was just ground-mounted solar photovoltaics, thus requiring additional support.

These economic analyses underscore how farmers that prioritize financial returns could sell their land to a developer or lease it for solar, whereas farmers that prioritize revenue but also farmland will forego substantial revenue or require local or federal government subsidies to convert to an agrivoltaic system. The economic analyses conducted to-date do not account for non-market values and thus cannot incorporate other benefits to society such as providing food security and clean water, nor do they account for farmers who value ecosystem services and would prioritize a less profitable agrivoltaic system or farmers who value traditional farming culture and would eschew any form of solar energy, agrivoltaic or otherwise.

Livestock

With respect to livestock and other agrivoltaic systems that require additional panel elevation, increased infrastructure results in non-trivial capital investments. For instance, a pilot solar array in Australia that was mounted high enough for cattle required an additional 60% investment compared to the cost of standard ground-mounted solar and thus was considered less economically attractive (Bowen and Chudleigh 2024). This is why sheep grazing can be economically enticing because solar arrays typically require little or no modification in terms of infrastructure expenses. In particular, sheep grazing on solar fields saves the solar developer substantial money that would otherwise be allocated to quarterly mowing, even after accounting for the additional infrastructural needs to manage the sheep (Bowen and Chudleigh 2024). In Australia, sheep grazers reported benefits of grazing solar fields that included additional income from leasing their land to solar developers, free pasturing of sheep on solar fields, more grass during drought conditions as the panels allow for better growth, and maintenance of wool and sheep health quality (Bowen and Chudleigh 2024). Indeed, a pilot study in southern Australia in similar climatic conditions to those in eastern Washington successfully established lamb forage under two existing solar arrays; modeling suggested that the microclimate conditions and pasture growth associated with ground-mounted solar arrays could provide economically-viable sheep production beyond the other co-benefits mentioned above (Gill et al. 2024). An economic analysis of a meat sheep and cattle ranch in Canterbury, New Zealand found the agrivoltaic project on ~0.5% of the property was financially viable for grazing livestock beneath the panels and providing substantially more income than just the agriculture (Vaughan et al. 2023). However, this analysis also found lower tradeoffs for just doing a solar project without the dual use of agriculture. The study also modeled a dairy case study but found that the land asset for dairies was higher than for meat animals, concluding that the dairy would lose value by any conversion to solar energy.

An economic analysis in Australia studied the net present value of a 250-acre solar facility over a 30-year period for grazing beef cattle or meat sheep flocks with varying degrees of added development costs beyond typical ground-mounted solar costs and given varying levels of livestock stocking rates because of panel infrastructure (Vaughan and Brent 2024). In general, both cattle and sheep grazing under panels will be profitable, even at higher stock reduction rates and low-to-medium added development costs, when on high productivity land. As land productivity decreases, the added development costs and reduced stocking rates dramatically limit the value of solar grazing, particularly with cattle given the higher additional upfront costs of raising panels higher. If the livestock owner (rather than the solar operator) has to make some initial investment into infrastructure at the solar facility, longer-term leases are needed to make the economic situation viable for the grazer. The researchers concluded that solar grazing is likely most economically viable on medium-to-high quality grazing lands and situations where stocking density can remain higher. Even so, this analysis was based on information from relatively few solar grazing facilities.

A cost-benefit analysis on dairy cattle grazing beneath solar panels studied the agrivoltaic scenario of creating solar grazing for dairy cattle and the counterfactual of converting dairy farmland into typical ground-mounted utility-scale solar arrays and integrating sheep (rather than cattle) grazing for vegetation control (Brenth 2024). The switch from cattle to sheep results in a 17-fold reduction in agricultural revenue. The analysis also assumes that it is impractical to convert the entire field into agrivoltaic arrays and uses up to 2% of the available land for elevated panels. This study assumed the placement of the panels in non-irrigated (dryland) portions of the fields, with the rest of the fields retaining irrigation for forage production. Ultimately, the study found that the levelized cost of energy of the cattle agrivoltaic system was 15% higher than the standard solar system, requiring a higher power purchase agreement of at least 10% to make the project financially feasible, although the projects would be profitable if selling to the wholesale electricity market.

Most economic modeling of solar grazing has occurred in Australia and New Zealand, and so it is unclear how these translate to the U.S. market, particularly Washington's context. Even so, this body of research suggests that solar grazing can be economically viable, particularly on higher productivity grazing lands and will likely necessitate only deploying solar arrays on a small proportion of pastureland.

Summary

A conclusion shared across economic studies is that, although agrivoltaics projects can be economically viable from an agricultural standpoint, they are typically not as profitable as direct conversion to a standard single-use utility-scale solar array (Chae et al. 2022, Trommsdorff et al. 2023, Vaughn et al. 2023, Buzzelli 2024, Pandey et al. 2025). Indeed, the financial incentive for solar developers to facilitate farming beneath panels is very low given how profitable energy production is (Chalgynbayeva et al. 2024). As such, other non-monetary values – such as rehabilitating exhausted land (i.e., ecovoltaics) - would be considered for non-agrivoltaic projects, or farmers and society might value agrivoltaics because it keeps all of a property in production. Further, for some high-value agricultural products like dairy, setting aside some land as single-use solar or agrivoltaics may never be marketable compared to maintaining land in forage production for dairy cows (Vaughn et al. 2023), although more work is needed in the U.S. context, particularly in western states like Washington. Critically, assessing the economics of agrivoltaics is challenging currently – particularly with production systems like orchards – given how few examples exist to study. The economic viability of agrivoltaics for different crops and livestock, at different production scales, and in different geographies will become clearer when more projects are built and operational (Trommsdorff et al. 2023). Finally, although agrivoltaics are more expensive than standard ground-mounted solar, they are cheaper than rooftop solar infrastructure.

Social Science

Beyond economic analyses, a growing body of research is targeted at understanding how farmers, rural communities, and the broader public understand and feel about agrivoltaics. This research is informative because social scientists have illuminated a mismatch between technological arguments about how relatively little land is needed to meet our energy needs and social considerations of whether converting agricultural land for energy uses disrupts a community's sense of place, including their material, financial, social, and emotional connections to land (Moore et al. 2022). Importantly, farmers view farming as part of their identity, particularly an identity with an ethical duty to conserve the land. In some agricultural communities, even switching crop types can be viewed as a betrayal of the local agricultural culture and heritage, even without solar (Moore et al. 2022). Quantitative social science surveys of technical, NGO, and social opposition respondents from 14 countries emphasized the substantial lack of consensus that exists in rural communities around agrivoltaics, even if the technology is meant to mediate tension between ground-mounted solar and farming (Cotton et al. 2025). Some groups are generally opposed to any solar on farmland (agrivoltaics or not) whereas others believe agrivoltaics can provide rural financial stability, mediate environmental instability, and reduce land use conflicts (Cotton et al. 2025).

A perception survey of fruit and vegetable farmers in California and North Carolina – two states with high agricultural productivity and solar energy potential – found that nearly half of farmers showed interest in agrivoltaics with the largest number of respondents expressing neutral sentiments towards agrivoltaics (Cuppari et al. 2024). Interestingly, most farmers had positive perceptions of solar energy in general and believed solar energy production is profitable. Only half of farmers expressed concern that an agrivoltaic system would reduce crop production, however 75% of farmers expressed concern that upfront costs would make agrivoltaics prohibitive. Market conditions and other farmers (more so than family, friends, academics, banks, or other factors) were the primary factors influencing respondents' decisions about their farming practices, underscoring how profitability as well as peer considerations matter in influencing agrivoltaic uptake. Critically, the statement that farmers most strongly agreed with was "I would keep farming even if selling solar power provided me with enough income to live" and the statement farmers most strongly disagreed with was that "farming is just a job". These results highlight the strong identity that farmers have as agricultural producers, why ground-mounted solar is strongly contentious among farmers as a threat to identity, and how agrivoltaics could mediate some of that tension, particularly if solar energy production is framed as an additional revenue stream rather than fully replacing agriculture due to the profit differences (Cuppari et al. 2024).

Focusing on Pinal County, Arizona, Swanson et al. (2025) assessed whether agrivoltaics is a more socially acceptable form of solar energy development in rural landscapes than typical solar energy deployment. Semi-structured interviews found deep opposition to converting farmland – particularly higher quality farmland – into solar energy. Although some farmers expressed interest in selling or leasing land to solar developers, this interest produced feelings like anxiety and betrayal to the local community with a view from many farmers that "land is worth more than converting it to an alternative source of energy". Arizona farmers view farming as an essential component of identity – not just an occupation – and understand it as a way of life (Swanson et al. 2025). Compared to general solar development, agrivoltaics was viewed with more optimism about preserving the agricultural industry. The Arizona farmers surveyed noted that industrial farming tends to use machinery that is getting bigger over time, thus limiting agrivoltaics for crops that require large tractors and other machinery. We note the same issue is true in Washington (personal communication from Andrew Nelson). However, these producers expressed enthusiasm for agrivoltaics for any crop that is harvested by hand. Solar developers surveyed in Arizona were skeptical of agrivoltaics for financial reasons (Swanson et al. 2025).

A social acceptance survey of multiple groups (local representatives, energy section, environmental and wildlife conservation, agriculture, research, etc.) of stakeholders in an apple region of Germany found generally strong acceptance for orchard agrivoltaics (Golz and Larisch 2024). In particular, community members are used to seeing large built structures over orchards for hail netting; the added potential value of solar infrastructure was appealing to these community members. The farmers surveyed suggested that extreme weather, increasing land competition, rising lease prices, and crop protection would encourage agrivoltaic adoption for orchards. In general, across sectors, local opposition and a distaste for changing landscapes was viewed as a likely factor inhibiting agrivoltaic adoption. This study noted that a true public perception study of agrivoltaics is currently challenging given the rarity of agrivoltaics and their diverse contexts and designs. A similar social science survey in Spain assessed how individuals felt about maintaining a viticultural landscape, creating a photovoltaic landscape, or vineyard agrivoltaics (Arias-Navarro et al. 2023). Survey respondents significantly preferred maintaining a viticultural landscape over a photovoltaic one. Even so, the majority of respondents preferred land use that combined vineyards and photovoltaic installations with most respondents acknowledging that this option was the most sustainable. Most respondents favored allowing solar arrays on vineyard land with some limitations, roughly one third of respondents prefer landscapes comprised of just vineyards and would prohibit solar on these lands, and only

<3% were in favor of solar without restrictions. In general, respondents preferred constraining photovoltaic installations to smaller land footprints and dispersed throughout vineyard land rather than as continuous arrays. Almost no respondents believed a solar array monoculture was the most sustainable use of land. Interestingly, a survey of Italian farmers and other agriculture-related professionals (engineers, lawyers, and businesspeople) found that the greatest perceived strength of agrivoltaics was its land use efficiency where only 15-20% of respondents believed that improved growing conditions and economic diversification were strengths (Di Domenico et al. 2025). ~25% of these respondents highlighted a dependency on incentives, initial upfront costs, and an impediment to agricultural production as weaknesses of agrivoltaics as were impacts to viewsheds and regulatory uncertainty.

A workshop where New Zealand beef cattle, dairy cattle, and sheep farmers discussed agrivoltaics found that producers underscored the value of agrivoltaics for diversified income and potentially advancing electrification for their operations as well as value for improving animal welfare and thus animal production (Vaughn et al. 2023). An interesting finding was producers' suggestion that agrivoltaics could enhance their social license to keep farming by improving public perception of farming. Farmers valued the environmental and animal welfare benefits of agrivoltaics beyond the potential direct value to their operations. Identified risks included restrictions on current and future use of their land, especially given 30-year lease. Farmers identified barriers such as upfront costs, the fact that dairy land is more profitable than subdividing for solar, and inexperience managing solar projects, and regulatory and neighbor perception uncertainty.

The body of social science research suggests that agrivoltaics may be a way to meaningfully broker solar energy deployment in agricultural landscapes and communities. Although there is rarely consensus within or between farming communities about solar energy in general and agrivoltaics specifically, studies repeatedly show a curiosity about and interest in agrivoltaics. Continued social science research as agrivoltaics are further deployed will help understand how this approach is shaping community identity and perceptions of solar energy.

Science Summary – Biological, Economic, and Social

Although there are examples of successful agrivoltaic operations, the weight of the science to-date illustrates a more complex picture surrounding the potential for agrivoltaics. The body of research on agrivoltaics points to crops and geographies where agrivoltaics may be more suitable and other contexts in which it is not. For Washington state, science suggests that cautious optimism about the feasibility of agrivoltaics for some agricultural production may be warranted. Below we highlight the biological, technological, economic, and social feasibility for agrivoltaics based on the best available science to-date.

Biologically, many crops (e.g., many grains, some vegetables) are too shade intolerant to be viable under the shading produced by agrivoltaics. Other crops (some vegetables) are sufficiently shade tolerant to have no yield reduction or small, but still marketable, yield reductions of sufficient quality. A small number of crop types (tree fruit, berries, grapes) will actually have equivalent or improved yield and/or quality under agrivoltaics due to shading benefits. Little data suggests drastic improvements to livestock production and no research suggests that agrivoltaics dramatically limits forage or livestock production, although sheep and cattle appear to show signs of improved wellbeing under solar panel shade. It is noteworthy that crops that tolerate or benefit from agrivoltaics can vary in their success under agrivoltaic systems as a function of regional or local climate, soils, variety, and other conditions, making generalization challenging.

Technologically, many crops like cereal grains, soy, and some vegetables are substantially reliant on heavy mechanization or irrigation infrastructure such that they are not easily suitable for agrivoltaics, even if the crop might tolerate from the shade. Some of these crops may be amenable for widely spaced vertical bifacial panels or particularly intensive raised solar infrastructure, but these are not economically scalable given current technology. Other crops can tolerate or benefit from agrivoltaics biologically but are often – though not always – mechanically harvested in ways that, without significant technological innovation, prohibit agrivoltaics. For instance, grapes and berries can biologically benefit from agrivoltaics but, in Washington, are often harvested using machinery that straddles crop rows rather than moving in between rows, prohibiting overhead solar. Other crops like tree fruits can have synergies with agrivoltaic infrastructure, allowing the solar panel pilings to replace trellis infrastructure and the panels themselves can replace shade cloth. Smaller diversified farms may more nimbly navigate technological limitations that constrain larger operations.

Economically, it will almost always be most economically efficient to convert agricultural land to standard ground-mounted solar, particularly given the increased row spacing and additional infrastructure needed for agrivoltaics. Some crop types cannot be made economically viable under an agrivoltaic system given current knowledge. Other crops that are biologically and technologically viable can also be economically viable under an agrivoltaic system given the proper proportions of standard agriculture and agrivoltaics on a property as well as an amenable policy landscape. Because there are few agrivoltaic projects to study, economic viability research is limited and should not be under- or overinterpreted. Growing research suggests that consumers might be willing to pay a premium for agrivoltaic-grown produce, suggesting benefits both for small, diversified farmers (e.g., at farmers markets, through community supported agriculture [CSA]) as well as larger-scale farmers selling across the country and internationally. Notably, agrivoltaics are more expensive than standard ground-mounted solar arrays but still markedly cheaper than rooftop solar.

Socially, direct conversion to solar will consistently cause conflict for most rural communities, even if individual farmers recognize the value of solar energy for maintaining land under family ownership or providing sufficient revenue. Notably, social science research shows that individuals in rural communities are not uniform in their perceptions of solar and agrivoltaics. Agrivoltaics cannot entirely remedy the tension between solar development and rural communities; even so, agrivoltaics have been shown to ease that tension as a form of supporting farmers' agricultural identity, maintaining rural character, diversifying revenue, and keeping land in agricultural production. Some crops like tree fruit or dairies are already infrastructure intensive and may not conflict with perceptions of the rural aesthetic.

Mapping

Statewide Potential

Agrivoltaics

To understand how much land is potentially suitable for agrivoltaics in Washington we employed a first principles mapping exercise. Here, this means that we focused on (1) the biological suitability of a given crop type to agrivoltaics and (2) proximity to energy infrastructure. With respect to crop suitability, our analysis cannot account for crop variety (e.g., blueberries vs raspberries, Honeycrisp vs Granny Smith apples) or agricultural practices such as whether and what type of mechanization or trellising is used. Even so, we are able to assess irrigation types. Although we measure information on photovoltaic potential for each farm field, we assumed the granularity of siting decisions will rely more on landowner willingness, zoning, and other decision-making rather than small or moderate differences in energy potential among sites. With respect to proximity to energy infrastructure, agrivoltaics projects hypothetically do not need to be grid-connected if they are only serving on-site energy needs. However, we assume that most agrivoltaic projects will be larger and connected to the grid. Of those, projects are more likely to be sited and built if they are close to substations and so we map agrivoltaic suitability based on proximity substations. We provide an ancillary assessment of agrivoltaic potential near transmission lines; however, we assume that energy projects that directly tie into transmission lines will be rarer as they depend on the available capacity of those lines and they will likely be smaller and thus less economical.

For crop data, we used the Washington State Department of Agriculture's (WSDA) land use layer[8]. WSDA's dataset is based on multiple data sources including drive-by surveys, producers' information, and the US Department of Agriculture (USDA). We preferred the WSDA dataset over USDA's cropland data layer[9] because WSDA relies more on observations and reporting of crop types whereas USDA infers crop types based on imagery and therefore has higher uncertainty. Even so, we note that WSDA data are also not infallible. For instance, the crop group 'vegetable' likely includes legumes which, depending on the crop variety, are not always amenable to agrivoltaics. Based off our literature review, we categorized crop groups into amenable or unamenable to agrivoltaics. Amenable crop groups included pasture, berries, orchards, vineyards, vegetables, herbs, and melon. Crop groups that we classified as unamenable for agrivoltaics included crops like cereal grains or forages, either because these are not shade tolerant or because they require such a high degree of mechanization that they are unlikely to function in agrivoltaics without substantial innovation (Pandey et al. 2025; personal communication from Andrew Nelson). WSDA's crop layer also includes data on the irrigation style. We classified each field as to whether it had 'high' or 'low' intensity irrigation. High and low in this case do not refer necessarily to the volume of water applied by the degree of infrastructure needed that might interfere with deploying solar arrays. Low intensity irrigation included styles such as no irrigation, sprinklers, or rill irrigation whereas high intensity irrigation included systems like pivot irrigation, gun irrigation, or wheel-line irrigation. We next measured the shortest distance from each agricultural field to

---

[8] https://agr.wa.gov/departments/land-and-water/natural-resources/agricultural-land-use
[9] https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php

energy infrastructure using substation and transmission line datasets produced by the US Department of Homeland Security.

We further integrated two datasets – PVout and PVR – into our analysis. PVout is a dataset produced by the World Bank that characterizes the practical photovoltaic output of a given area (The World Bank 2020). PVout simulates how solar resources are converted to electricity by integrating the effect of local air temperature, terrain horizon, and albedo in addition to the hypothetical photovoltaic system's tilt, configuration, shading, soiling, etc. PVout's units are kWh/kWp which can be interpreted as the kWh of energy produced for a hypothetical kW peak of installed capacity. PVout allows users to compare the relative solar resources of a given area. PVR - 'Productivity, Versatility, and Resilience' - is a dataset provided by American Farmland Trust that represents the agricultural potential of an area that is best suited for long-term cultivation (American Farmland Trust 2022). PVR is an index that incorporates soil productivity and capacity, land cover and land use, crop type, and length of the growing season. The analysis to generate PVR relied on agricultural experts to weigh and rank the analysis' inputs with the goal of identifying priority lands that will produce food and other crops over the long term. PVR is on a scale of 0 to 1, with higher values reflecting more productive agricultural land.

We summarized PVout and PVR for each WSDA farm field. We chose not to use these datasets to prioritize agrivoltaic potential in our analysis. We did this because we ultimately concluded that individual siting decisions for agrivoltaics projects will rely more on landowner interest, community and jurisdictional support, economic viability of a project, suitable crop types, and proximity to energy infrastructure. Even so, we provide PVout and PVR data in our web map so that users can explore those inputs on their own. Further, we use PVout and PVR for several statistical analyses. Specifically, we statistically analyzed (1) whether PVout and PVR were inherently correlated, i.e., do fields with higher farmland productivity tend to consistently have higher or lower photovoltaic potential and (2) whether relative PVout and PVR values vary as a function of crop type, region of the state, and the degree of irrigation intensity. The second question is valuable for understanding whether agrivoltaics inherently targets farmland that are more or less productive. For instance, our analysis focuses on fields that use lower intensity irrigation infrastructure; does this tend to concentrate agrivoltaic potential in higher productivity farmland?

Pivot Corners

Other common features of agricultural landscapes are pivot corners. On fields that use center pivot irrigation, the corners of those fields often remain unirrigated. Consequently, these corners of pivot irrigated fields often remain uncultivated and, in many cases, remain unused for any purpose. One potential use for pivot corners is for solar arrays. Although placing solar energy on pivot corners would be considered colocation and not agrivoltaics, we mapped solar potential on pivot corners to complement our analysis of agrivoltaic potential in Washington. Pivot corners presumably would represent a lower conflict form of solar siting as productive land is not displaced, although local ordinances may still prohibit solar energy siting on pivot corners as the parcels are still agricultural land. Solar energy placed on pivot corners may also be more economical than agrivoltaics because, hypothetically, the solar arrays could be built with similar specifications – and therefore cost considerations – as standard utility-scale solar.

No dataset exists to-date on where pivot corners are. We mapped pivot corners in ArcGIS Pro by implementing a series of selections and geoprocessing on the WSDA Crop 2022 spatial dataset. Generally, within WSDA's dataset, while pivot corners are not called out as such, they are grouped with non-pivot irrigated croplands. For this report, pivot corners were mapped essentially as the portion of non-pivot irrigated croplands that overlap a quarter mile buffer of pivot irrigated croplands. Non-feasible areas were erased from those overlap areas. Non-feasible areas include streams and waterbodies, wetlands, railways, roads, building surrounds, sloped areas over 15 degrees, and major public lands managed for ecological and cultural resource protection. We also summarized PVout and acreage for pivot corners and calculated distance to substations and transmission.

Results

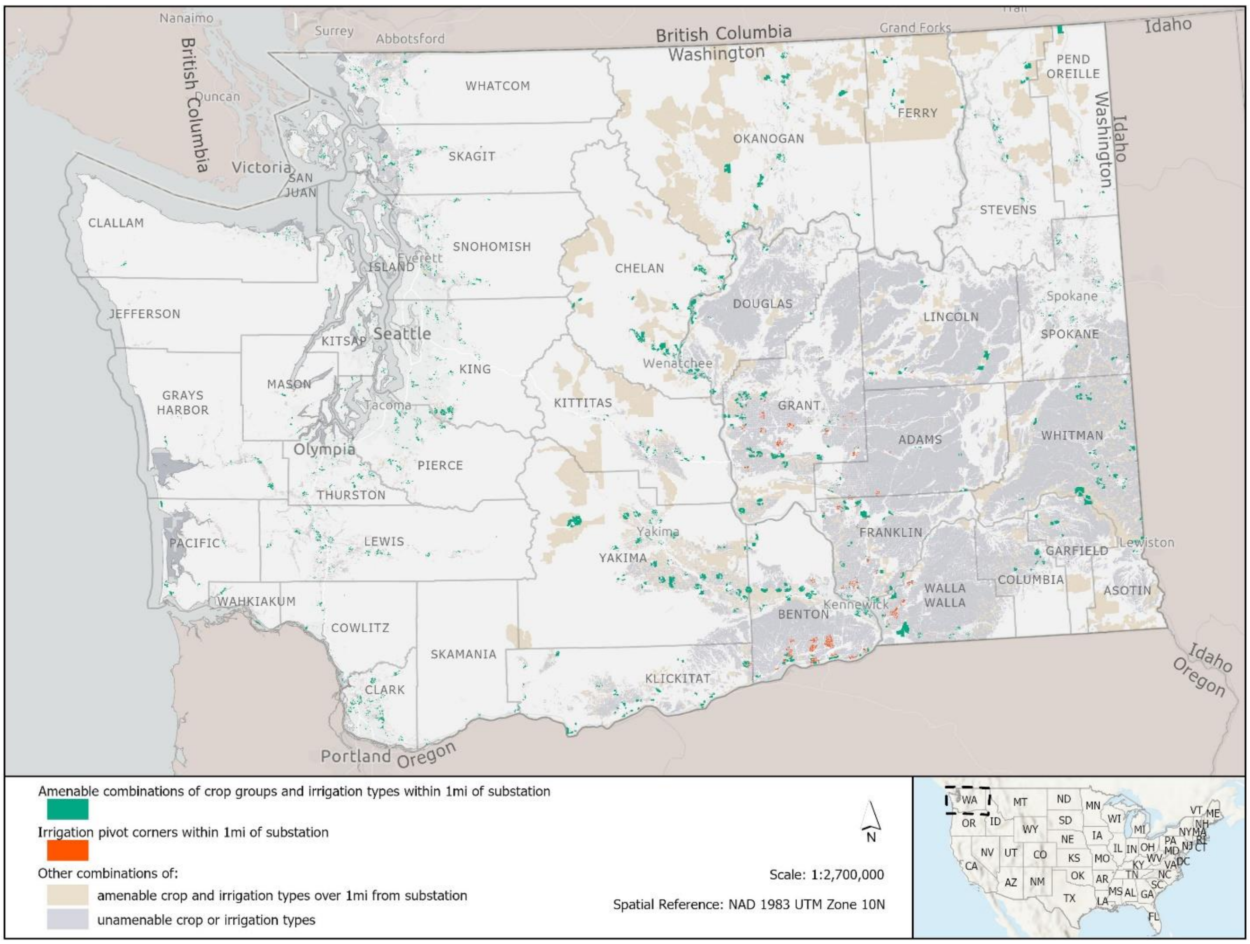


Figure 7. Washington-wide agrivoltaic land potential within 1-mile of substations. Also shown are pivot corners for potential colocation of solar on farmland.

We identified > 204,000 acres of land in Washington that is hypothetically amenable for agrivoltaics given crop types, degree of irrigation, and proximity to substations (Figure 7). If those acres were fully built out, this amount of land could hypothetically have capacity to generate 20.5 - 41 GW of energy, based on general estimates of 5-10 acres needed per MW of solar energy development (Ong et al. 2013). Pastureland represents 60% of this agrivoltaic-amenable land area, with most of that falling in central and eastern Washington (Figure 8). After pastureland, orchards comprise > 20% of amenable agrivoltaic land statewide (Figure 8, Table 1). Despite the seemingly large acreage of potentially suitable agrivoltaic land in Washington, those ~205,000 acres represent only ~11% of all land within 1-mile of substations and ~13% of all farmland within 1-

mile of substations in Washington. Although most land in Washington near a substation is some form of agricultural land – including cropland, pastureland, shellfish, commercial tree, etc. - proportionally little of that farmland is amenable for agrivoltaics.

Over half of the potential agrivoltaic land within 1-mile of substations is pastureland. If we assume only up to 5% of pastureland could be developed as agrivoltaics (see Vaughan et al. 2023, Brenth 2024), then we identified nearly 87,000 acres of cropland and pastureland amenable for agrivoltaics. This would equate to 8.7 - 17.4 GW of potential solar energy capacity from agrivoltaics. In this more plausible scenario, pastureland represents less than 10% of amenable agrivoltaic land in Washington. In contrast, orchard lands represent 50% of all agrivoltaic land potential in the state with nearly all of it falling in central and eastern Washington (Figure 8, Table 1). Even under this scenario, pastureland represents 20% of potential agrivoltaic land in western Washington with berries and vegetables contributing over 70% of the amenable agrivoltaic land in that half of the state. Multiple counties have over 2,000 acres of orchard within 1-mile of a substation: Grant (> 11,000), Chelan (> 6,000), Yakima (~ 6,000), Douglas (~5,000), Benton (~4,000), Okanogan (> 3,000), Franklin (> 3,000), and Walla Walla (> 2,000).

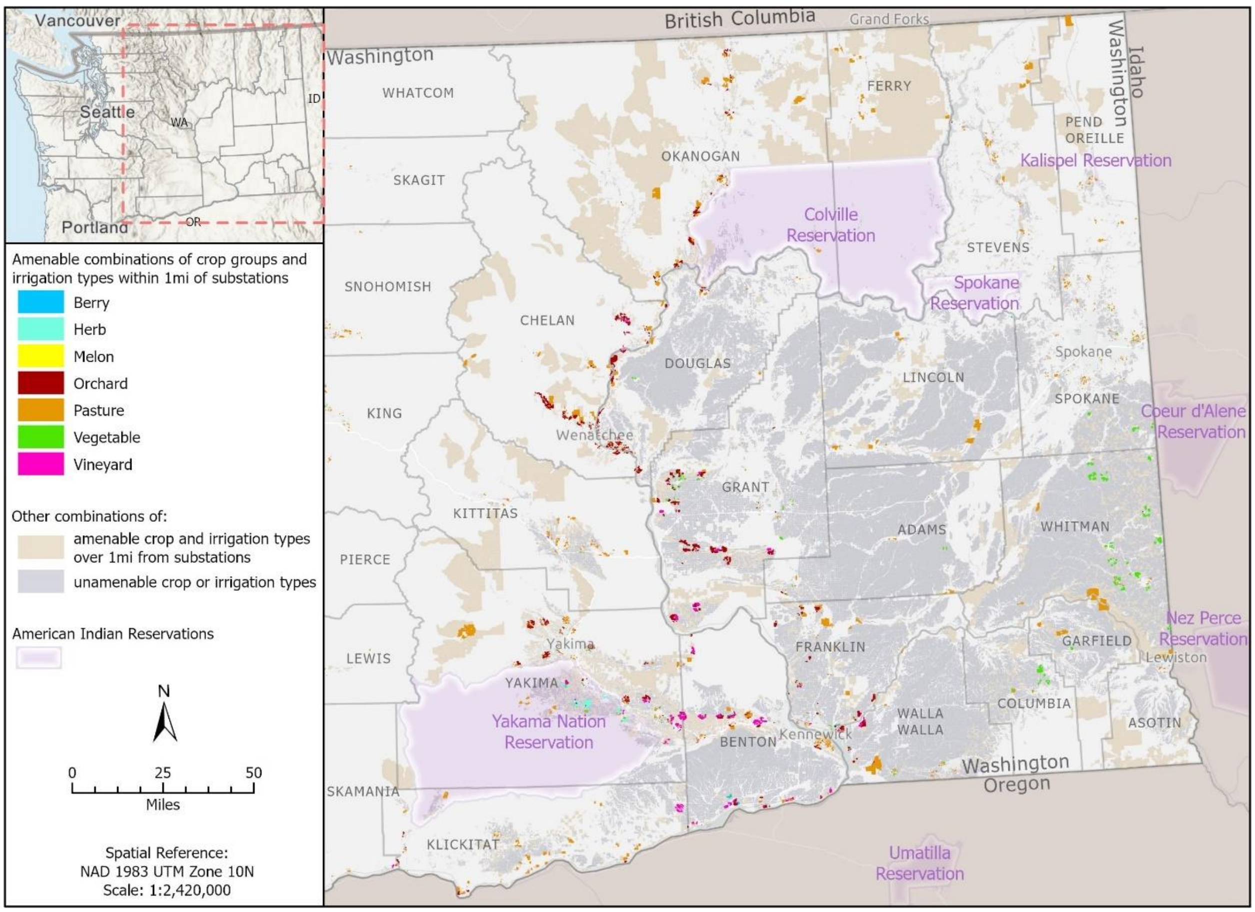


Figure 8. Agrivoltaic land potential occurs primarily in central and eastern Washington. Colored farm fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and which is within 1-mile of a substation. Gray farmland represents either crop types that are not amenable to agrivoltaics and/or farmland with high intensity irrigation infrastructure that restrict agrivoltaics. Tan farmland represents crop types that are hypothetically amenable to agrivoltaics, but which are further than 1-mile from substations.

Table 1. Acreage of potential agrivoltaic land by crop group and either side of Washington

	Crop Group	Acreage	% of state side	% statewide	Energy Capacity (GW)
Central & Eastern Washington	Berry	1,080	1 (1)	1 (1)	0.1-0.2
	Herb	6,107	4 (8)	3 (7)	0.6-1.2
	Orchard	42,375	25 (53)	21 (49)	4.2-8.5
	Pasture	92,978 (4,649)	55 (6)	45 (5)	9.3-18.6 (0.5-0.9)
	Vegetable	13,528	8 (17)	7 (16)	1.4-2.7
	Vineyard	11,808	7 (15)	6 (14)	1.2-2
Western Washington	Berry	2,824	8 (39)	1 (3)	0.3-0.6
	Herb	5	0 (0)	0 (0)	~0
	Orchard	201	1 (3)	0 (0)	~0
	Pasture	31,026 (1,551)	84 (21)	15 (2)	3.1-6.2 (0.2-0.3)
	Vegetable	2,534	7 (35)	1 (3)	0.3-0.5
	Vineyard	164	0 (2)	0 (0)	~0

*Numbers in parentheses reflect a re-analysis assuming a maximum of 5% of pastureland will be used for agrivoltaic solar grazing

**Energy capacity is estimated based on an assumed 5-10 acres / MW needed for solar arrays based on NREL data

Our mapping assumed that agrivoltaic feasibility was technically greatest within 1-mile of substations. We consider this a relatively conservative estimate of agrivoltaic feasibility because presumably some projects can be built further than 1-mile from substations. However, we also created a more ambitious agrivoltaic suitability map based on amenable crops with low intensity irrigation that are within 1-mile of transmission lines. This is because some projects – particularly smaller projects – have potential to directly tie into transmission lines without needed connect to a substation. Further, it is possible that future substations are more likely to be constricted in proximity to existing transmission corridors. This analysis yielded a cumulative 942,214 acres of farmland, representing a potential 94-188 GW of solar energy capacity (Figure 9; Appendix Table 1). Potential agrivoltaic land near transmission also dominates in central and eastern Washington (Appendix Figure 5). This farmland drops to 351,707 acres (35-70 GW of solar energy capacity) if we assume only 5% of pastureland can be built out) that is within 1-mile of transmission lines and suitable for agrivoltaics. This acreage includes > 145,000 acres of orchards in central and eastern Washington (15-30 GW) and > 13,000 acres (1.3-2.7 GW) of berry land in western Washington that are within 1-mile of transmission. The acreage of potential agrivoltaic land within 1-mile of transmission is 4.5X the acreage of potential agrivoltaic land within 1-mile of substations. Because these numbers are exaggerated, we focus on the mapping outcomes within 1-mile of substations but recognize that these estimates may be relatively conservative.

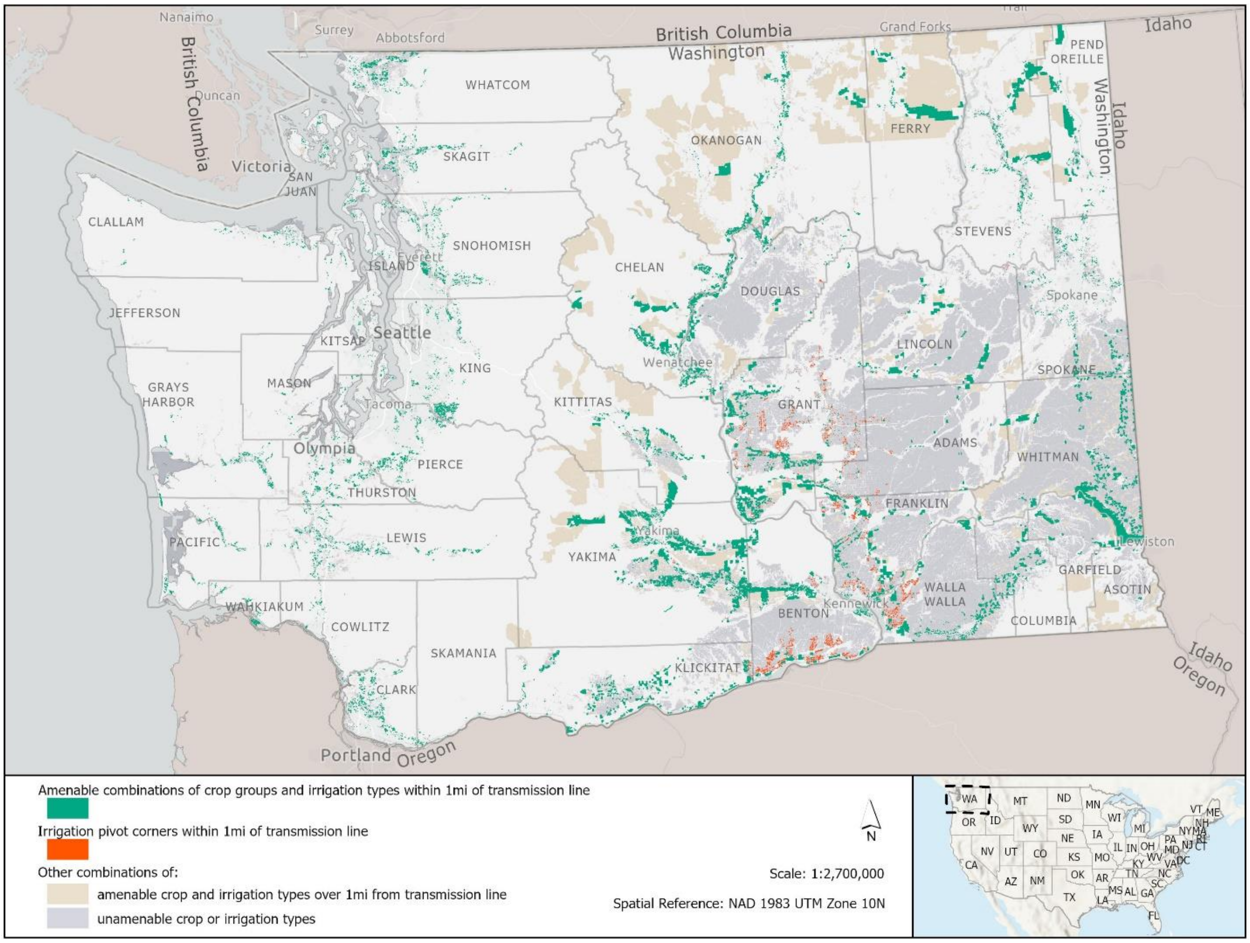


Figure 9. Washington-wide agrivoltaic land potential within 1-mile of transmission. Also shown are pivot corners for potential co-location of solar on farmland.

These mapping results should be interpreted as a relatively conservative high-level assessment of agrivoltaic land potential. For instance, although 'orchard' is a dominant crop category in this analysis, our data cannot distinguish between apples, pears, cherries, and other tree fruit nor between varieties of apples and whether existing orchards are trellised or not. Similarly, 'vegetable' is a broad category of crops and fields could encompass crops that differ in shade tolerance, and which might be hand harvested or mechanically harvested. Importantly, some vegetable crops like potatoes, onions, and carrots are rotated with cereal grains and so these croplands may be inadequately classified and therefore not suitable for agrivoltaics. Given these limitations, the amount of potential agrivoltaic land may be lower. That being said, our analysis of agrivoltaic land potential in proximity to transmission lines (rather than just proximity to substations) provides a much bigger landscape for agrivoltaic potential.

Based on the farmland that is within 1-mile of substations and suitable for agrivoltaics, we produced maps for most counties (Appendix Figures 6-19). The maps emphasize how – once accounting for crop viability and proximity to energy infrastructure – only a relatively small amount of Washington's farmland is suitable for agrivoltaics. Indeed, much of Washington's farmland is "blank space" on the maps with respect to agrivoltaic suitability. This is because most of Washington's landscape near energy infrastructure is agricultural land that is not suitable for agrivoltaics. In particular, farmland within 1-mile of substations that is classified by WSDA as 'cereal grain' encompasses 184,313 acres in eastern Washington and 7,996 acres in western Washington; cumulatively, cereal grain represents ~1/4 of all land statewide and nearly 1/3 of land in eastern Washington that is near substation. Land within 1-mile of substations classified as 'hay/silage' encompasses 69,650 acres in eastern Washington and 38,040 acres in western Washington; hay/silage encompasses nearly ~15% of land statewide that is near energy infrastructure and 12% and 19% of the land in eastern and western Washington, respectively. Thus, roughly 40% of all land in Washington that is within 1-mile of a substation is represented by cereal grain or hay/silage, two agricultural systems that are not suitable for agrivoltaics given the high degree of mechanization. Even though cereal grain is the most prominent land cover type near substations, the cereal grain land near substations represents only a small fraction of all cereal grain land in Washington. Specifically, the > 190,000 acres of cereal grain within 1-mile of substations is just under 5% of all cereal grain land. Even so, irrigated cereal grain is typically rotated with vegetable crops like potatoes, onions, and carrots. This land alone equates to roughly 18-36 GW of solar energy capacity, which would represent conversation without maintaining agricultural production beneath solar panels.

Grant, Yakima, and Benton counties have the largest cumulative area of potential agrivoltaic acreage in Washington, each with over 10,000 potential acres if we do not consider pastureland, although these three counties each have several thousand acres of potentially suitable pastureland (Appendix Figures 6-8). Solar energy potential (PVout) and farmland productivity (PVR) are both variable within and between counties (Table 2). Notably, although PVout potential differs between western and eastern Washington, PVout potential for all the agrivoltaic fields are similar between crop types within either side of the state. This perhaps is not surprising as farmland demands sufficient solar resources and is therefore non-randomly distributed on the landscape. For context, the yearly monthly PVout values for some of the sunniest areas of southern California or Arizona are ~1,900-2,100 kWh/kWp.

Statistical analyses found that neither PVout nor PVR were consistently associated with irrigation intensity, side of the state, or crop type (Appendix Figures 20-23). Similarly, PVout and PVR were not consistently correlated, meaning that agricultural fields with higher PVout potential did not consistently have higher or lower PVR (Appendix Figure 24). For both PVR and PVout, linear models and likelihood ratio tests identified three-way interactions between predictor variables as the best supported models for both PVout and PVR. For PVout, solar potential tends to be highest for farm fields in eastern Washington, although there is some variation in this pattern. For instance, fields with lower intensity irrigation infrastructure for vineyards and pastureland have overlapping PVout across the state. The intensity of irrigation infrastructure is similarly not consistently associated with PVout. For instance, in eastern Washington, lower intensity irrigation infrastructure has higher PVout compared to higher intensity irrigation infrastructure whereas the opposite is true for vegetable fields in that side of the state. For PVR, lower intensity irrigation infrastructure fields tend to have higher PVR than higher intensity irrigation infrastructure fields in eastern Washington but not western Washington. In general, western Washington berry fields have some of the highest PVR for farmland across the state with respect to crop types that are amenable for agrivoltaics. In contrast, pastureland - on average - has some of the lowest PVR across the state. However, the variability in PVR is particularly high for pastureland and much of the lower PVR land may be public lands that also hold high wildlife and cultural value. Further, PVR is not consistently correlated with PVout among crop types. In eastern Washington, PVout tends to be positively correlated with PVR, i.e., agricultural fields with higher solar resources tend to also be more productive cropland for most agrivoltaic-relevant crop types. This pattern is less pronounced in western Washington, although it appears to be true for western Washington berry lands.

Table 2. Photovoltaic potential (PVout) and farmland productivity, versatility, and resilience (PVR) for suitable agrivoltaic fields

		PVout			PVR		
	County	min	mean	max	min	mean	max
Central & Eastern Washington	Adams	1492	1506	1516	0.23	0.42	0.72
	Asotin	1418	1432	1491	0.12	0.26	0.56
	Benton	1376	1511	1560	0.10	0.54	0.79
	Chelan	1117	1456	1547	0.12	0.58	0.79
	Columbia	1384	1474	1498	0.15	0.56	0.90
	Douglas	1372	1479	1550	0.10	0.59	0.79
	Ferry	1234	1315	1374	0.12	0.29	0.56
	Franklin	1471	1499	1517	0.09	0.55	0.72
	Garfield	1344	1451	1511	0.12	0.17	0.43
	Grant	1439	1524	1545	0.12	0.65	0.79
	Kittitas	1458	1535	1568	0.12	0.36	0.62
	Klickitat	1316	1497	1588	0.09	0.54	0.98
	Lincoln	1317	1459	1510	0.13	0.28	0.51
	Okanogan	1334	1428	1509	0.09	0.54	0.79
	Pend Oreille	1178	1283	1348	0.18	0.38	0.61
	Spokane	1321	1372	1433	0.10	0.42	0.83
	Stevens	1257	1317	1366	0.11	0.41	0.68
	Walla Walla	1405	1458	1507	0.09	0.48	0.94
	Whitman	1404	1449	1488	0.12	0.44	0.88
	Yakima	1318	1539	1573	0.10	0.63	0.79
Western Washington	Clallam	1146	1243	1289	0.15	0.50	0.75
	Clark	1154	1241	1267	0.15	0.47	0.99
	Cowlitz	1181	1204	1248	0.26	0.55	1.00
	Grays Harbor	1137	1167	1202	0.36	0.49	0.69
	Island	1204	1249	1284	0.18	0.40	0.68
	Jefferson	1153	1201	1239	0.16	0.36	0.51
	King	1116	1196	1257	0.15	0.34	0.65
	Kitsap	1194	1213	1222	0.24	0.34	0.58
	Lewis	1149	1197	1270	0.20	0.52	0.95
	Mason	1186	1208	1240	0.15	0.37	0.51
	Pacific	1139	1190	1213	0.18	0.50	0.76
	Pierce	1159	1208	1246	0.17	0.51	0.85
	San Juan	1257	1294	1319	0.08	0.39	0.59
	Skagit	1162	1223	1279	0.14	0.50	0.78
	Skamania	1196	1335	1400	0.13	0.38	0.63
	Snohomish	1086	1179	1247	0.14	0.52	0.78
	Thurston	1178	1197	1211	0.19	0.37	0.70
	Wahkiakum	1167	1185	1199	0.25	0.41	0.69
	Whatcom	1143	1252	1310	0.22	0.58	0.96

*Photovoltaic potential is based on World Bank PVout data. PVout is presented as monthly yearly averages with units as kilowatt hours per installed kilowatt peak of installed capacity per year (kWh/kWp). Shading represents the spectrum within each minimum, mean, and maximum column across counties from lowest (darker) to highest (lighter) PVout values

** PVR is on a zero-to-one scale where one represents high productivity, versatility, and resilience. PVR incorporates data on soil suitability, land cover and land use, and food production type and incorporates rankings based on expert surveys.

Agrivoltaic Land Ownership

We also include a high-level analysis of the distribution of landownership acreage pertaining to agrivoltaic potential. WSDA provides GIS data at the field level. However, landowners often own multiple fields and so agrivoltaics projects for a given landowner could cross multiple fields We used Regrid’s parcel ownership GIS data to identify the ownership of each agrivoltaic-potential field. Regrid’s data are consolidated from city and county jurisdiction information and, as such, data for each jurisdiction are reported in a diversity of ways. For instance, the Washington State Department of Natural Resources could be reported as “State of WA – Dept of Natural Resources” or “Washington State – DNR", among others, and so we attempted to consolidate various ownership synonyms across parcels. We focused this analysis on 11 counties in central and eastern Washington: Benton, Chelan, Douglas, Franklin, Grant, Klickitat, Lincoln, Okanogan, Walla Walla, Whitman, and Yakima. Our goal was not to holistically characterize land ownership for agrivoltaic-potential fields in Washington, but to begin assessing the range of potential project sizes, number of landowners, public versus private ownership, etc.

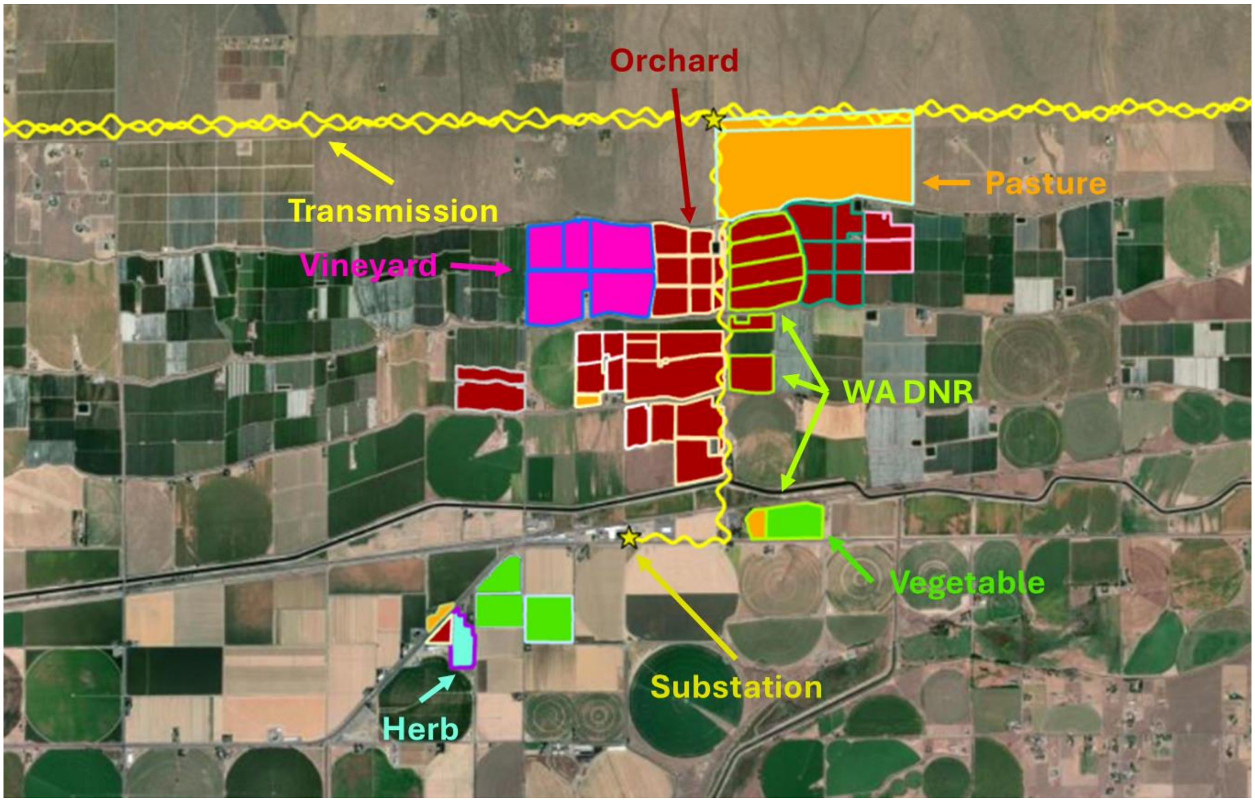


Figure 10. Example of varied farm ownership for potential agrivoltaic land in Washington. Colors within farm fields represent crop types whereas the color of farm field borders reflect different landowners. In this case, there are ~1,270 acres of potential agrivoltaic land around the two substations with 14 different landowners. In this example, the Washington State Department of Nature Resources (WA DNR) owns 174 acres, largely of orchard land. Three other landowners own 180 acres or more in this area whereas most of the landowners have 50 acres or fewer. Private landowners are not identified here for privacy.

The ~115,000 acres in the 11 counties we assessed represent ~70% of the potential agrivoltaic land identified east of the Cascade crest. We identified ≥ 2,500 landowners across this acreage. The mean landowner's potential agrivoltaic acreage is 41.8 acres whereas the median was 7.3 acres. Landowners may own adjacent fields that are further than 1-mile from substations. This means that most potential agrivoltaic land is owned by landowners who own only a few dozen acres, most of whom own less than 10 acres in proximity to substations. Indeed, over ~85% of landowners own fewer than 50 acres. The implication of this is that utility-scale agrivoltaic developers may rely on a small number of landowners who own larger land areas and who are interested in transitioning a large portion of their land into agrivoltaics, or they will have to coordinate agrivoltaics projects across multiple adjacent landowners (Figure 10). Alternatively, these data might suggest that many agrivoltaics projects will tend to be smaller projects.

Over 10% of (roughly 14,460 acres) of the agrivoltaic potential in these 11 counties is owned by the federal government, the state of Washington, or cities and counties. The remainder is owned privately, typically by LLCs or individuals and families. Almost all agrivoltaic potential land in this area that is owned by cities, counties, or the federal government is designated as pasture by WSDA. The U.S. government owns over 7,000 acres and the state of Washington owns roughly 5,600 acres in this area. Ownership data by agency are rarely clear, although Washington State DNR clearly owns over 2,700 acres concentrated across five counties (Benton, Franklin, Grant, Klickitat, and Okanogan). Of this DNR land, over 1,000 acres are orchards (Figure 10) and roughly 800 acres are vineyards. Another roughly 900 acres in Benton County is owned by Washington State (although it is unclear by which agency) and, of this acreage, over 500 is orchard, roughly 240 is berries, and over 100 is vineyard. State-owned land may therefore represent an opportunity for exploring agrivoltaics.

Pivot Corners

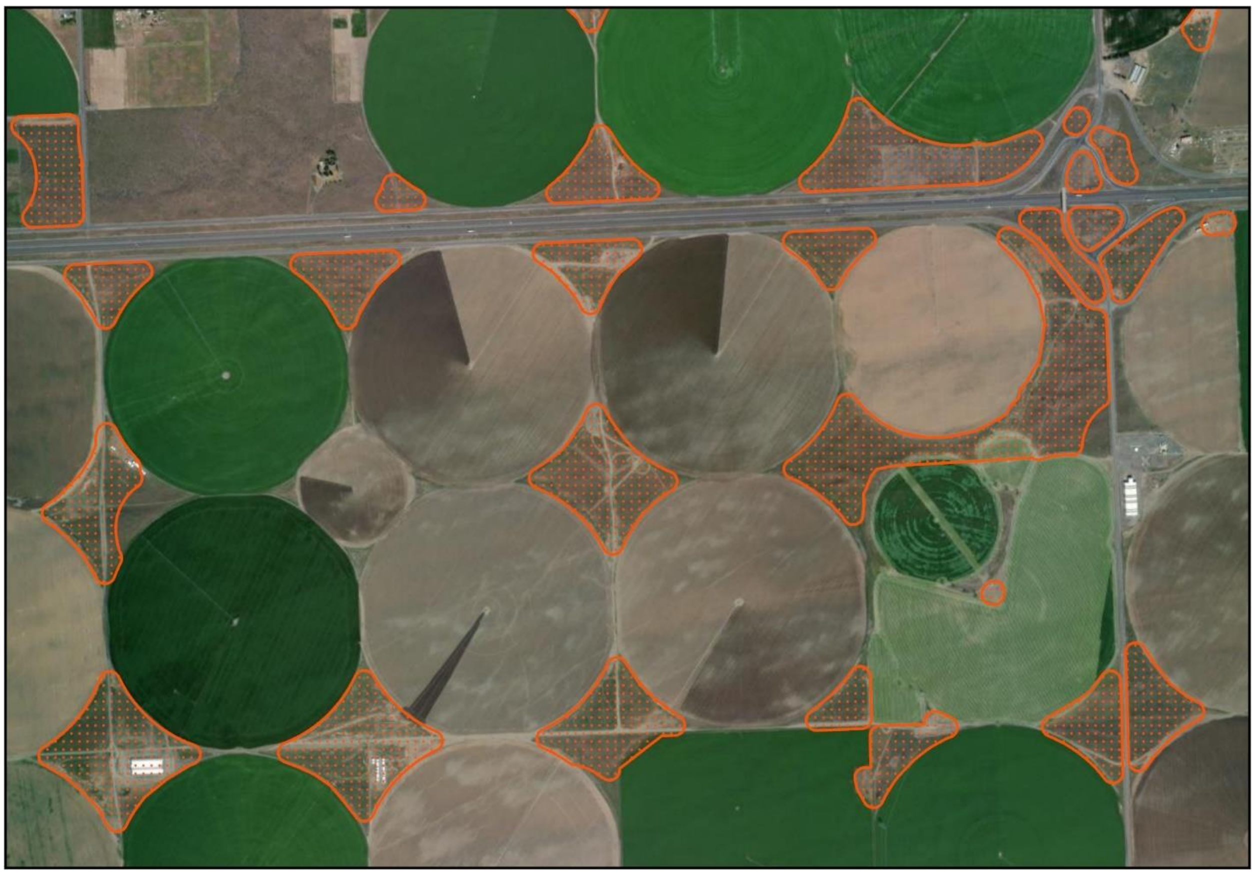


Figure 11. Pivot corners identified by mapping. This land is typically an unused artifact of center pivot irrigation and may be amenable for solar energy development.

We successfully identified pivot corners through our mapping exercise (Figure 11). In total, we mapped 371,170 acres of pivot corner land across Washington state (Figures 7 and 9), with >80% concentrated in Benton, Grant, and Franklin counties. Within 1-mile of substations, we identified 43,674 acres of pivot corners, representing 4.4-8.7 GW of potential solar energy. Roughly 45% of those 43,674 acres are in Benton County, 24% in Grant County, 14% in Walla Walla County, and 11% in Franklin County. The average PVout for these pivot corners is ~1,470-1,540 kWh/kWp, in line with the PVout trends for agrivoltaic lands in central and eastern

Washington. Although not agrivoltaics, pivot corners represent a complementary form of solar colocation on farmland that may be socially and technologically easier to deploy than agrivoltaics. Even so, the amount of pivot corner area in proximity to substations is roughly half of what we conservatively estimated for agrivoltaics. As such, agrivoltaics represents a greater amount of land area for potential solar deployment.

Web Map

We created an interactive web map that allows users to study agrivoltaic potential by identifying farmland that is amenable or not, vary proximities to substations and/or transmission lines, summarize acreage by counties, clicking on fields to explore attributes, etc. Users can begin in the web map with the full array of WSDA agricultural fields but filter out crop types and irrigation systems that are not amenable. We have coded each field as "amenable" or "unamenable" for agrivoltaics based on whether the crop type should function well in agrivoltaics based on our literature review. We also coded each agricultural field's irrigation type as "low" or "high" intensity based on the degree of infrastructure needed and whether it is likely to interfere with agrivoltaics. Thus, users can replicate our final mapping outcome by selecting only fields that have "amenable" crops and "low" irrigation infrastructure. Further, our analysis conservatively assumed that agrivoltaic projects – particularly larger projects – would be more likely to be constructed near electrical substations. We used a proximity of 1-mile to substations for our analysis. However, users may have higher or lower tolerances for distances to substations and/or transmission lines and can select fields with varying proximities to that electrical infrastructure.

The 'Washington Agrivoltaics Map Viewer' (Figure 12) web map can be found here or by searching 'WAFO Agrivoltaics Map Viewer" on arcgis.com.

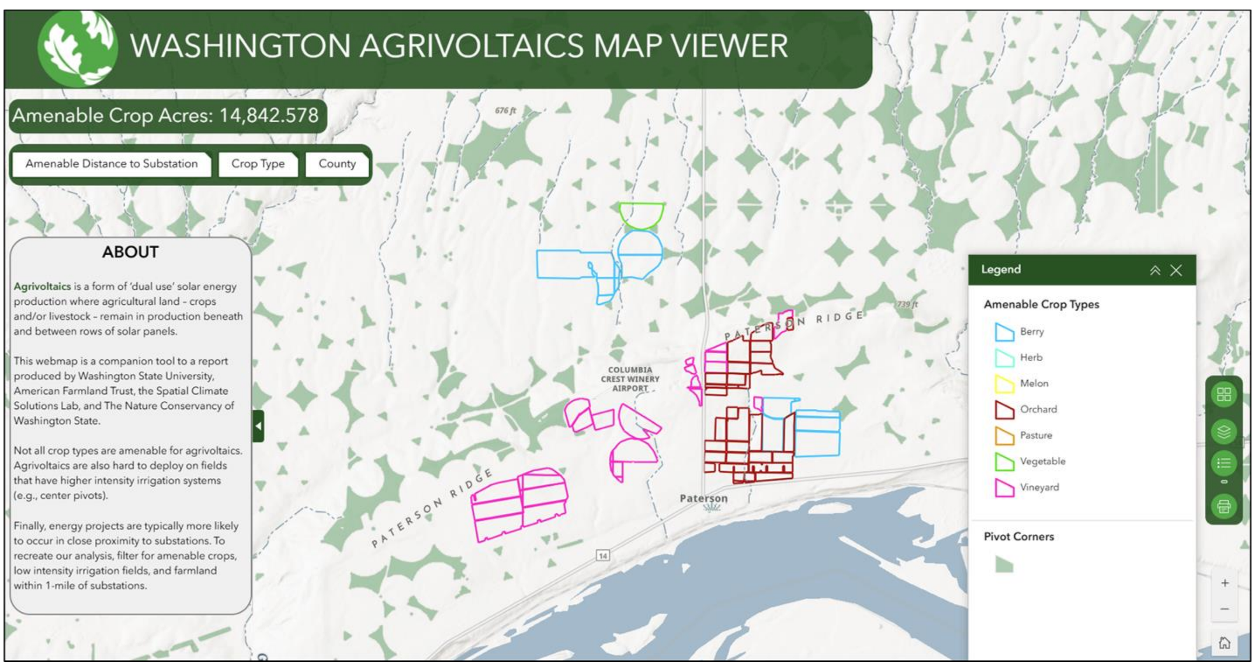


Figure 12. The Washington Agrivoltaic Map Viewer allows users to explore potential agrivoltaic lands, pivot corners, and other farmland at various distances from substations and transmission lines.

Tribal Lands and the Columbia Basin

There is an emerging recognition that agrivoltaics could contribute to Tribal energy and food sovereignty as well as economic opportunities (Moore and Lobell 2024). We briefly expand upon our agrivoltaics results in the broader context of Tribal land and, particularly, agriculture throughout the Columbia River Basin. Our mapping found some agrivoltaic potential within the boundaries of the Yakama Nation, although those lands are not necessarily currently under Tribal ownership. Beyond this, there is little other amenable land for agrivoltaics within reservation boundaries. However, there may be amenable agrivoltaic land within reservation boundaries that is further than 1-mile from substations and/or transmission lines.

More broadly, the Columbia River and its tributaries have catalyzed a dramatic agricultural economy in a relatively arid, hot portion of the Pacific Northwest. Understanding whether agrivoltaics are equally suitable in other regions of the Columbia Basin, particularly in Idaho and Oregon, could facilitate agrivoltaic deployment throughout the region, especially if farmer resources and developers had a larger market to operate in. Further, agrivoltaics may provide an opportunity to support Washington's and Oregon's commitments to Tribes in the Columbia River Basin as part of the Six Sovereign's Columbia Basin Restoration Initiative which has a strong emphasis on the region's energy portfolio. The Columbia River Intertribal Fish Commission (CRITFC) represents the four mid-Columbia River Tribes (the Confederated Tribes and Bands of the Yakama Nation, the Confederated Tribes of the Umatilla Indian Reservation, the Confederated Tribes of the Warm Springs Reservation of Oregon, and the Nez Perce Tribe) in advancing watershed protection and restoration throughout the Basin to restore abundant salmon fisheries. CRITFC's 2022 Energy Vision for the Columbia Basin includes a recommendation to promote demonstration projects that advance dual use solar, particularly on agricultural lands (Columbia River Intertribal Fish Commission 2022).

Although USDA's agricultural GIS dataset is less accurate than WSDA and does not include data on irrigation systems like WSDA does, it provides comparable agricultural land data across our region. We took a similar first principles approach to understanding agrivoltaic potential throughout the Columbia River Basin. Specifically, we focused on agricultural lands within 1-mile of substations across the Basin and removed crop types that typically rely on intensive mechanization and/or irrigation. Because we do not have irrigation data with USDA, it is likely we are including fields with crop types that are amenable to agrivoltaics, but which currently have intensive irrigation infrastructure. As such, our USDA analysis likely overestimates agrivoltaic potential.

Our calculations included an assumption that only 5% of pastureland would reasonably be built out as agrivoltaics. Given that assumption, we identified roughly 132,000 acres of potential agrivoltaic farmland – dominated by pasture and orchards (Appendix Figures 25 and 26) within 1-mie of substations across the Columbia Basin, equal to 13.2-26.5 GW of solar energy. This relatively conservative estimate would increase greatly if we estimated agrivoltaic potential within 1-mile of transmission lines instead of substations or if we increased the distance from substations that a project could be developed. We found that Washington state represents over 60% of the agrivoltaic potential in the Columbia Basin. We identified almost 83,500 acres (8.3-16.7 GW) of agrivoltaic potential land within Washington's portion of the Columbia Basin. This estimate is similar to our statewide estimate for Washington state which makes sense because most agricultural land in Washington is in the Columbia Basin. This also suggests that, despite its limitations, the USDA data provide a reasonable approximation of agrivoltaic land, and that any overestimation in agrivoltaic potential is limited. Orchards make up over 60% of the agrivoltaic potential of Washington's agrivoltaic estimate in the Columbia Basin, followed by vineyards at 17%, pasture at 11%, and herbs at 8%.

Within Oregon's portion of the Columbia Basin, we identified nearly 33,000 acres (3.3-6.6 GW) of agrivoltaic potential. Roughly 55% of Oregon's agrivoltaic potential is orchards, followed by pasture at 29%, and vegetables and herbs at roughly 5.5% each. Idaho has nearly 11,500 acres (1.1-2.3 GW) of agrivoltaic potential, 60% of which is in the form of pastureland even after we consider only 5% of pastureland to be available for agrivoltaics. In Idaho, the remaining agrivoltaic is dominated by herbs (24%) like hops and vegetables. We are cautious with estimates of herbs and vegetables because there is likely lower accuracy in classifying these crop types from USDA data. Montana, Wyoming, and Nevada all have relatively small potential agrivoltaic contributions by area, almost all of which comes from pastureland.

Comparison to other Solar Energy Mapping

Several solar mapping tools already exist that are relevant to Washington. We briefly outline the approach and content of these maps to distinguish what our mapping analysis provides, particularly with respect to agrivoltaic potential

Least Conflict Solar: Washington State University's Energy Program released a report and associated GIS mapping tool: 'Least Conflict Solar Siting on the Columbia Plateau'. The goal of this work was to identify areas on the Columbia Plateau for solar energy siting that are low conflict for ecological conservation, farming, and ranching. This was a stakeholder-based mapping tool that integrates input from iterative stakeholder meetings with fuzzy logic modeling. The output of this work is a map comprised of ~62 acre-sized pixels. The goal of the work was to guide energy siting, particularly to lower-conflict areas. This work did not include any consideration of agrivoltaics and so it is largely assumed that agriculture and energy deployment are in tension.

DNR Clean Energy Parcel Screening: The Washington State Department of Natural Resources (DNR) produced its 'Clean Energy Parcel Screening' tool which focuses on DNR-owned parcels that may be considered for potential energy development. The exact process DNR used to generate their Parcel Screening is not clear. Even so, DNR's website states that they pre-screen thousands of parcels for potential energy generation capacity, potential conflicts (e.g., environmental or cultural), and through consulting stakeholders. DNR notes that the identified parcels require further collaboration with the agency before any solar projects are considered.

Notably, from our analysis, only 26 of the over 600 parcels available in DNR's screening tool occur within 1-mile of substations and therefore most parcels are likely not easily developable for solar energy. Of those 26 parcels, most have a current use described as grazing, dry agriculture, or conservation. Agrivoltaics was unlikely considered during DNR's decision making for this screening tool which likely explains why the DNR-owned orchards and other agrivoltaic-amenable cropland we identified are not in the screen.

TNC's Power of Place: The Nature Conservancy developed various "Power of Place" projects, one for California, the western states, and U.S.-wide. Although the underlying methodology included spatial data, the goal of Power of Place was not to provide an energy siting tool *per se*. Rather, the goal was to model various decarbonization pathways and conservation trade-offs to understand what mechanisms various forms of energy deployment across an interconnected could be used to minimize displacing conservation lands and agricultural lands while meeting clean energy goals. The Power of Place report includes consideration of agrivoltaics and suggests that agrivoltaics can help the U.S. meet its energy needs. In its consideration of agrivoltaics, however, certain crops (e.g., potatoes) were included as amenable for agrivoltaics but are unlikely to be readily amenable given high mechanization needs. And other crops like apples were not considered because the science had not been developed yet.

Agrivoltaic Modeling

Introduction

Optimally or strategically designed agrivoltaics projects can generate synergies across both the agricultural and solar energy systems. In particular, crops that are susceptible to heat stress could benefit from the partial shade provided by solar panels in certain climates. Shading can also reduce evapotranspiration and increase water use efficiency in arid growing regions. Agrivoltaic systems will perform differently depending on the geographic location and photovoltaic design. While small-scale demonstration and experimental projects are critical for advancing agrivoltaic knowledge regionally, it is challenging to explore the entire design space or extrapolate agrivoltaic system performance across multiple growing regions or crops with experimental projects alone. Notably, the published literature establishing that agrivoltaic systems confer net positive yield or quality impacts to produce is still limited (Dupraz 2024). Model simulations of both electricity generation and shade impacts on crops in agrivoltaic systems can help bridge this gap by assessing both feasibility and scalability. Such approaches rely on coupling or integrating a solar photovoltaic system design model with a crop model (Campana et al. 2021; Bellone et al. 2024; Dinesh and Pearce 2016). Here, we explore how different photovoltaic system designs and geographic location impact the cost effectiveness of electricity generation, crop productivity or quality of crops that are most amenable for agrivoltaics in Washington, particularly apples and berries. To address the absence of both agrivoltaic or shade impact studies on apples, berries, or vegetables in Washington, we specifically sought to:

1. Develop tailored agrivoltaic designs for three farms across the state that currently grow or would consider growing leafy vegetables, berries, or apples
2. Quantify electricity generation, levelized cost of energy, and strawberry and lettuce productivity impacts of several agrivoltaic designs across representative berry and vegetable growing regions in Washington
3. Quantify electricity generation, levelized cost of energy, and apple sunburn risk reduction of several agrivoltaic designs across representative dessert apple growing regions in Washington

For apples, we compared the performance of three suitable photovoltaic system designs—higher density single-axis tracking, lower density single-axis tracking, and fixed tilt panels racked 13 feet over the rows of trellised apple trees. While the vast majority of new solar energy projects use single-axis tracking systems with the ability to control the panel tilt to allow for changes to the shading regime, fixed tilt systems are lower cost and may be more cost effective at higher latitudes. For strawberry and lettuce farms, we generated a standard single-axis tracking design elevated to 6 feet above ground and several fixed tilt designs that varied panel row spacing (pitch) and panel height. For designing these agrivoltaic systems, generating shade profiles below and between panels, and estimating photovoltaic electricity generation, we use an industry-standard commercial photovoltaic modeling software, PVsyst, which has been used in other agrivoltaic simulation studies (Dinesh and Pearce 2016; Hussain and Ghosh 2024). The resulting shade profiles were then used as inputs to a crop simulation model, STICS (Brisson et al. 1998; Dinesh and Pearce 2016), for modeling strawberry and lettuce productivity impacts in agrivoltaic systems. For modeling apple sunburn risk, we provided shade profiles as inputs to the Li et al. (2014) model.

Approach

Representative Site Selection

For strawberry and lettuce agrivoltaic simulations, we selected 15 locations across the berry and vegetable growing regions in the state using the WSDA crop distribution data, limited to agricultural land within 1-mile of existing substations (Figure 13). Locations were selected to achieve geographic representation across eastern and western Washington and across major agricultural counties. Sites within counties were selected based on the location with the highest concentration of berry or vegetable farms.

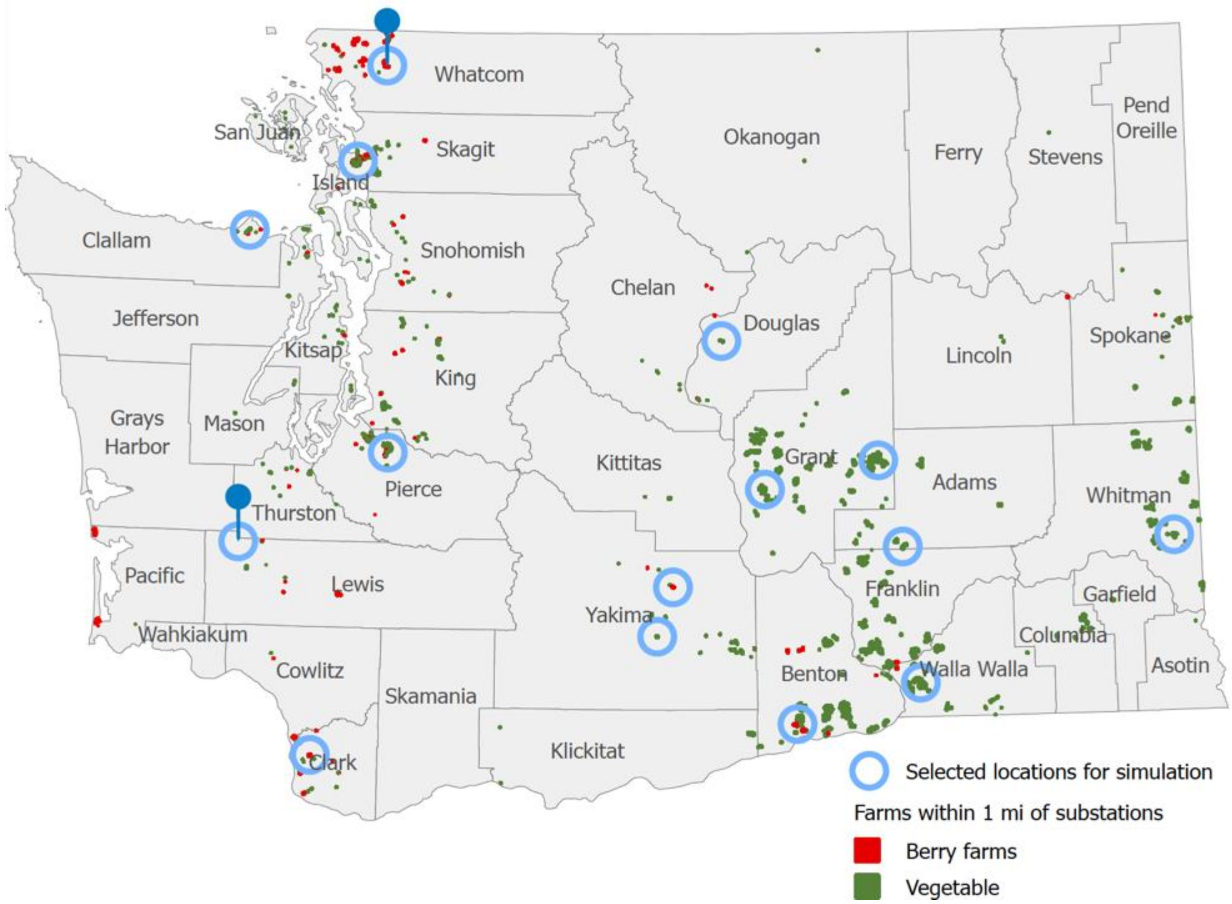


Figure 13. Locations for strawberry and lettuce simulations overlaid on WSDA crop distribution map showing locations of berry and vegetable farms within 1-mile of existing substations. The two map points in Whatcom and Lewis counties indicate the two pilot vegetable/berry farm locations, Small Acres (Whatcom county) and Centralia 43 (Lewis County), for which we generated site-specific designs.

For apple sunburn risk modeling, we applied a systematic process for selecting 10 representative locations across the dessert apple orchard growing region (central/eastern Washington). We began with daily meteorological data from the GridMET dataset, which provides 2.5-mi gridded surface weather and climate variables. We extracted data for 446 GridMET grid cells that overlapped apple orchard areas with at least 20 MW of estimated solar capacity based on a capacity density of 0.08 MW/acre (or half of the average ground mount density of 1.6 MW/acre). For each location, we calculated summary statistics over the 2020–2022 period for variables relevant to apple growth, sunburn risk, and solar electricity output including daily maximum and minimum temperature, wind speed, solar radiation, relative humidity, and precipitation. Metrics included means, variability (standard deviation), extremes, growing degree days, and counts of days above critical thresholds (e.g., TMAX ≥ 35°C). We normalized all metrics and applied k-means clustering to group the 446 locations into clusters ranging from 1 to 30. We chose 10 clusters as this was roughly around the elbow point in the variance change plot (Appendix Figure 27). To select a representative site from each cluster, we identified the location with the lowest combined distance to both the cluster centroid in standardized feature space and the geographic centroid of the cluster. This ensured that each selected site was both meteorologically and spatially representative of its cluster (Figure 14).

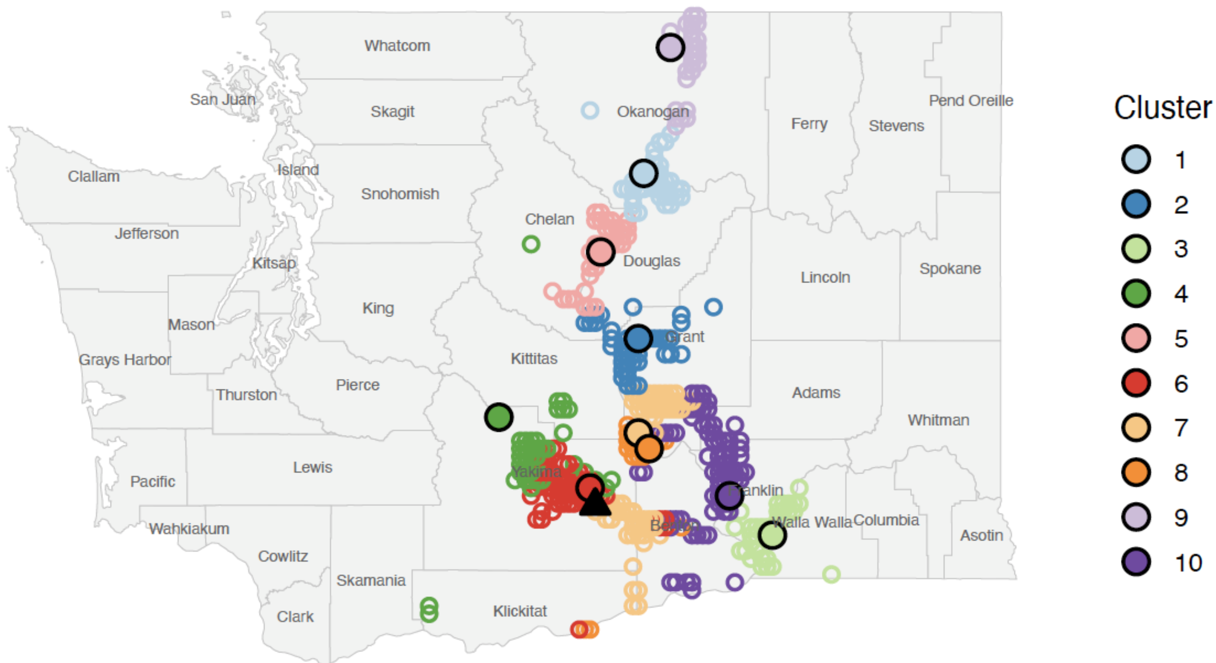


Figure 14. Ten representative locations of apple orchards chosen using meteorological metrics important to determining apple production and sunburn risk and solar electricity generation. Open colored circles represent the weather data locations with coverage across the eastern Washington apple growing region. Colored circles with black outlines indicate the representative site for each cluster. The black filled triangle indicates the location of the pilot apple orchard, Stonemetz Orchards, for which we generated a site-specific design.

Meteorological Data

We downloaded hourly weather data for the years 2013-2022 at representative locations for each orchard cluster from NREL's National Solar Radiation Database (NSRDB). The NSRDB is a free, high-resolution source of the three most critical parameters for solar analysis, Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI), and Direct Normal Irradiance (DNI). The NSRDB interpolates satellite and ground-level data to give accurate values of other important weather parameters with a 2.5 mi X 2.5 mi resolution throughout the contiguous United States and various international locations.

For the United States, data on the NSRDB covers years 1998-2024 at an hourly resolution. Weather measurements like temperature, wind speed, and humidity are measured at NREL locations throughout the country. These measurements are assimilated to the NSRDB's 2.5 mi X 2.5 mi resolution using NASA's Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) tool. For wind speed, which varies drastically at different heights above the ground and has a large impact on our fruit quality results, the NSRDB reports wind speed at 6.6 ft above the surface.

The following parameters were extracted from the weather data for use in the PVSyst model: ambient temperature, GHI, DHI, relative humidity, precipitable water, wind speed, and surface albedo. To allow for more accurate solar generation comparisons between years, all leap days were skipped during our data processing. Fruit quality simulations, as well as crop production simulations, are run using the NSRDB data, with adjusted GHI values according to the shading found during the solar modeling runs.

Agrivoltaic PV Array Designs

Table 3. Design specifications for the four variants for lettuce/strawberries farms simulations

	Low spacing	Medium spacing	High spacing	Tracking
DC Capacity	73.44 kW	59.84 kW	59.84 kW	80.92 kW
Area (acres)	0.203862 360	0.192001 311 kW/area	0.21312839 280 kW/area	0.21312839
Spacing (ft)	12.3	14.3	16.3	9.84
Row lengths (ft)	52.5 (2 rows side by side)	52.5 (2 rows side by side)	52.5 (2 rows side by side)	70.5
Number of rows	12 (2 rows side by side)	10 (2 rows side by side)	10 (2 rows side by side)	12
Height(s) (ft)	4, 5, 6	4, 5, 6	4, 5, 6	6

Table 4. Design specifications for the three variants for apple orchards simulations

	Single-axis tracking - low density (Var 1)	Single-axis tracking- high density (Var 2)	Fixed tilt - low density (Var 3)
DC Capacity (kW)	76.16	119.68	76.16
Acreage	0.3274146	0.3274146	0.2750283
# of PV Rows (by acreage above)	32	32	12
Length of PV Rows	41 ft	39 ft	69 ft

Solar Generation Modeling and Shade Profile Calculations

The software PVSyst was used to generate solar production and measure the solar flux reaching each crop. In PVsyst, solar flux can only be measured on solar panels, so segments of solar panels were placed in representative crop locations in the PVSyst 3D scene. In other words, we mimicked plants in our model by using solar panels beneath solar panels. The solar flux reported by PVSyst is the effective global flux, after calculating losses from object shading (labeled GlobEff in PVSyst's variable reporting). The lower panels were shaded by larger panel arrays, which varied in size, location, and tracking capabilities for each variant and farm simulated.

Measuring the difference in solar flux reaching the crops for each farm variant required three unique 3D scenes. The first of these scenes was a control, in which the solar panels representing the crops were laid flat on the ground. In the case of modeling apple orchards, the panels were lifted 4 ft above the ground to mimic a representative fruiting height. The second scene for each variant was just the planned PV array, without any "crop" panels. The final scene was the combination of both the first and second scenes, where the "crop" panels were placed below the PV array as a full agrivoltaic system. Measuring the average solar flux for these individual scenes allowed us to find the solar flux for the "crop" panels under shade. Multiplying the final scene (crop and PV) flux by the total DC capacity of the model and then subtracting the product of the second scene (only PV) flux and the DC capacity of that PV array, then dividing the result by the DC capacity of the first scene (only crop) allowed us to measure the change in flux of the crops under shade.

The PVSyst CLI tool was used to run batches of simulations through the pre-modeled 3D scenes. By using a Python script to make CLI calls, we were able to fully automate the process of collecting, simulating, and processing the irradiance and solar generation data for each variant studied.

Levelized Cost of Electricity (LCOE) Calculations

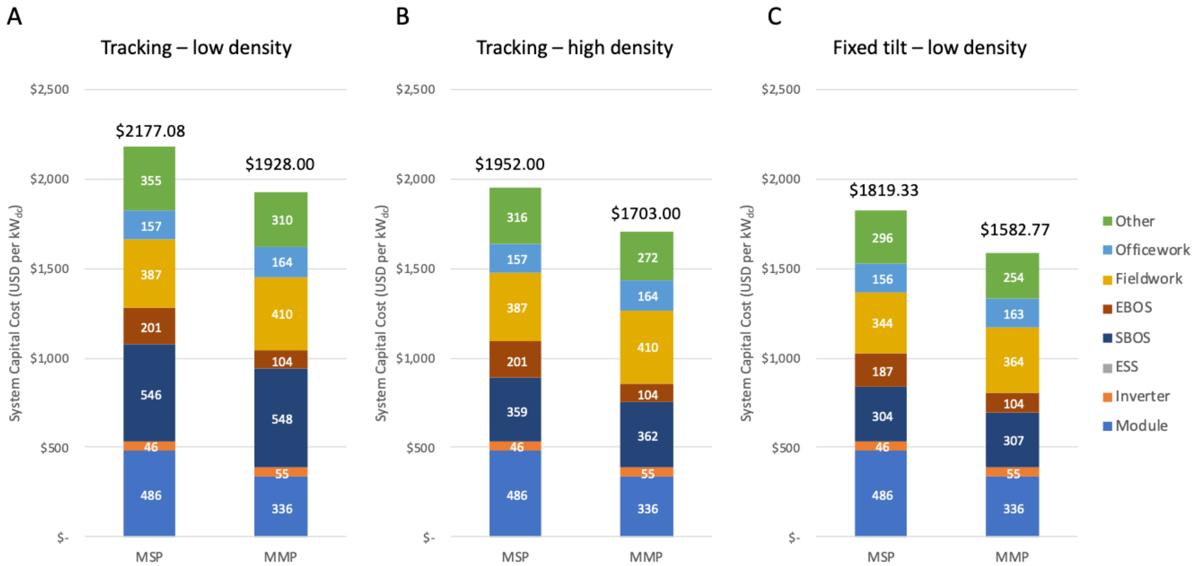


Figure 15. Capital cost estimates for each apple orchard system variant. MSP is the minimum sustainable price in a balanced, competitive market that a company can charge for its product or service and remain financially solvent for the long term. MMP is the Modeled Market Price or the actual price in the current market for the representative system being modeled. It differs from MSP due to short-term market distortions including supply-chain constraints and limited-term tariffs or subsidies. In this study we use the MMP for all LCOE estimates as this is more comparable with reported historical LCOE values. EBOS is the electrical balance-of-system (BOS) components (conductors, combiner boxes, circuit breaker, transformer) and the SBOS is the structural balance-of-system components (torque tubes, driven piers, module rails, fasteners).

Costs were generated using the Solar Photovoltaic System Cost calculator with agrivoltaic inputs from the US Department of Energy (Basore et al. 2024). The original PVSCM (PV system cost model) assumes a fixed tilt ground mounted system so we estimated multipliers for Structural Balance of System (SBOS) costs, Electrical Balance of System (EBOS) costs, fieldwork, and officework to account for the added costs associated with single-axis tracking systems and elevated (racked) panels. For elevated panels, we used select inputs from (Horowitz et al. 2020) for posts (piers) and horizontal tubing. See the Excel workbook (worksheet APV designs) linked here to see assumptions made for each design. For example, based on reported LCOE values for US projects, tracking systems cost on average \$0.2/W_{dc} greater than fixed tilt, or about 15-20% higher in capital costs (Seel et al. 2024). Thus, we applied a 15% multiplier on top of structural cost multiplier for elevated panels for single axis tracking designs. The resulting capital costs for each array design are in Figures 15 and 16. The LCOE of US projects built in 2023 (Appendix Figure 28) are provided here as reference point.

We used capital costs and fixed operations & maintenance costs from this adapted agrivoltaic cost calculator in a simple LCOE equation, assuming an interest rate of 4% and using the location and design specific capacity factors.

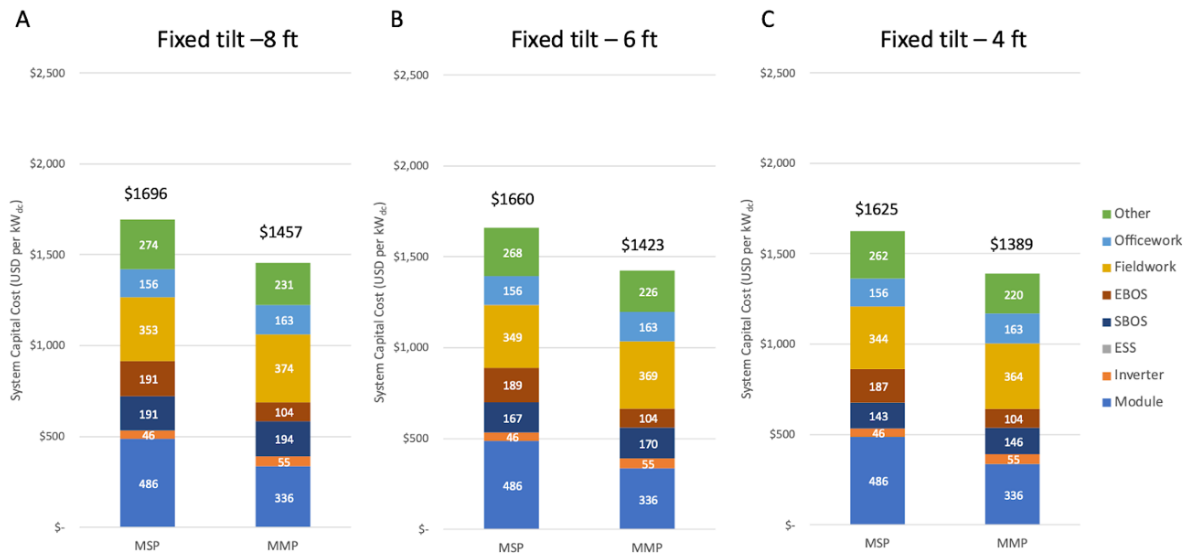


Figure 16. Capital cost estimates for medium spacing berry/lettuce farm variants at three panel heights. Costs were also estimated for low and high spacing variants at three panel heights (not displayed here). See Figure 15 for interpretation of figure and abbreviations.

Apple Sunburn Risk Modeling

To estimate sunburn risk in apple orchards, we simulated fruit surface temperatures using an energy balance model originally developed by Li et al. (2014) and operationalized in the R package 'agclimtools' (Pruett, 2021). This model has been used to estimate fruit surface temperature and sunburn risk (Ranjan et al. 2020, Savalkar et al. 2024). The model estimates fruit surface temperature using an energy balance approach, considering air temperature, wind speed, solar radiation, dew point temperature, fruit size, albedo, fruit and ground emissivity, sunlit portion, and surface conductance as inputs. The fruit surface temperature model employs the equation below to calculate the surface temperature, using all specified inputs.

$$T_{fs} + 273 = -\frac{\varepsilon_f \sigma \left(T_{fs} + 273\right)^4}{c_p g_a + \frac{\lambda g_w \rho_{air} \Delta}{P}} + \frac{R_{abs} + c_p g_a T_a + \frac{\lambda g_w \rho_{air} \Delta T_a}{P} - \frac{\lambda g_w \rho_{air} \left(e_s(T_a) - e_a\right)}{P}}{c_p g_a + \frac{\lambda g_w \rho_{air} \Delta}{P}} + 273$$

T_{fs} denotes the fruit surface temperature °C, T_a represents the air temperature °C, ε_f is the emissivity of the fruit surface, σ is the Stefan-Boltzmann constant, c_p is the specific heat capacity of the air, g_a is the boundary layer conductance of the turbulent heat transfer from the fruit surface (estimated from $g_a = 1.4 \times 0.135 \times \sqrt{\frac{u}{0.84 \times d}}$, where d is the diameter of the fruits), λ is the latent heat of vaporization, and g_w is the fruit surface conductance, ρ_{air} is the air density, Δ represents the rate of change in vapor pressure, R_{abs} Is the total incoming radiation (sum of shortwave and longwave radiation) in W/m2.

R_{abs} is calculated using the following equation:

$$R_{abs} = R_{ns} + R_{nl}$$

$$R_{ns} = \frac{Ad}{A} (1 - \alpha) R_s$$

$$R_{nl} = \varepsilon_a \sigma (T_a + 273)^4 + \frac{Ar}{A} \varepsilon_g \sigma (T_{gmean} + 273)^4$$

Where R_{ns} is the shortwave radiation, R_{nl} is the net longwave radiation, α is the reflectance of the apple fruit surface, which is assumed here as 0.6, Ad is the projected sunlit area, A is the whole fruit surface, Ar is the projected area exposed to reflected radiation, T_a and T_{gmean} are the air and ground temperature, and ε_a is the atmospheric emissivity (calculated using the following equation $\varepsilon_a = 1.24\, (\frac{e_a}{T_a})^{1/7}$) , ε_g is the ground emissivity.

Sunburn risk is identified when the fruit surface temperature threshold exceeds the variety-specific threshold. For our analysis here we have assumed the threshold is 43 °C which is relevant to Honey Crisp, a variety susceptible to heat and risk of sunburn damage (Kalcsits et al., 2017). In this model, we have simplified some of our assumptions, such as fruit size, albedo, and fruit surface conductance, as well as the assumption that ground temperature equals air temperature. The sunburn risk has been calculated for a fully exposed fruit surface (Ad/A = 1). In practice, they usually vary; specifically, fruit size varies with the growing phase and orchards, and albedo varies with color, growing phase, and the fact that the fruit surface is not always fully exposed to the sun. Our assumed parameters are listed in table below:

Model Parameter	Value
Fruit diameter (d)	0.26 (ft)
Ground emissivity (ε_g)	0.97
Fruit emissivity (ε_f)	0.95
Albedo/reflectance	0.6
Sunlit portion (Ad/A)	1
Ground lit portion (Ar/A)	0
Fruit surface conductance (gw)	$5.67 \times 10^{-8}\ (Wm^{-2}T^{-4})$

Crop Yield Modeling

The open-source software '*Simulateur mulTIdisciplinaire pour les Cultures Standard*', or STICS, was used to model the relative crop yields under agrivoltaic systems. STICS simulates crop production and soil chemical content using a variety of technical files, which specify crop management practices like irrigation, harvest dates, and fertilization schedules. STICS uses pre-parameterized crops to model biomass or fruit yield at harvest, which was used as a measurement of the impact of shading on crop production. Due to the complexity of crop parameterization, only the default parameters for existing crops in the STICS database were run.

Both lettuce and strawberries were used as target crops to study the effect of increased shading due to agrivoltaics on crop production. The suggested crop sowing and harvest dates of February 5th and June 30th were used to model strawberries, with fruit yield estimated in tons per hectare for 90% fruit water content. Fruit yield for modeled agrivoltaic sites was compared to the yield of unshaded crops in the same location to quantify the production tradeoff for agrivoltaics.

In order to study the benefit of agrivoltaics in different seasons, we ran three different crop cycles each year to model the effects on lettuce production. We chose the sowing and harvest ranges of March 1st to April 22nd, May 15th to June 6th, and August 1st to September 22nd. These dates spanned the growing season and allowed us more insight into the growth of a temperature-dependent crop. The lettuce yield at the end of the growing season was estimated in tons per hectare of aerial dry biomass at harvest.

We only varied the weather data input before each STICS run, leaving all other parameters identical. STICS requires daily inputs of temperature extremes, average wind speed, total GHI, rainfall, atmospheric CO2 content, and Penman PET. These inputs were aggregated over averaged from hourly NSRDB weather corresponding to each site. Yearly averages for the atmospheric CO2 content were found from NOAA's Global Monitoring Lab, and daily values for Penman PET were calculated using the Penman-Monteith equation and the average hourly relative humidity from the NSRDB weather. A Python script was written to collect the daily rainfall data from the nearest complete NOAA monitoring dataset radially.

To characterize the shading under each agrivoltaic system, the hourly GHI from the PVSyst simulations for each location were aggregated to daily values and inserted into the STICS weather files. Python code was written to automate this process for each shading variant and site location over an 11-year period. Crop yields were averaged and compared to unshaded variants to model the effect of shading on gross production.

Findings

Farm-Specific Agrivoltaic Array Designs

Centralia 43

Figure 17. Parcel map of Centralia 43 with the approximate location of the designed agrivoltaic system indicated with the yellow box.

Centralia 43 is a 43 acre protected farm located in Lewis County managed by the Black Food Sovereignty Coalition (BFSC) in partnership with the Washington Farmland Trust (Figure 17 and Figure 18). Jamese Kwele and Catherine Satava are the main stewards of the farm. They envision the farm serving as an incubator and training hub for Black farmers in western Washington. Using a portion of the farm for agrivoltaics seemed very well aligned with this vision. There is currently no crop production, but the unforested portions are currently grazed by cattle. Jamese Kwele and Catherine Satava expressed interest in a blueberry u-pick plot with some elderberry or apple trees for the eastern parcel (yellow box in Figure 17), which is on a south facing slope. We designed a 5.5-acre agrivoltaic system that would be appropriately sized for blueberries underneath and between panels. However, due the lack of a parameterized blueberry crop model, we estimated strawberry and lettuce yield impacts of panel shading for each system design as proxies.

The Centralia 43 farm location is unique due to its slanted crop-growing region on a south-facing hill. The most suitable placement for agrivoltaics is a 12.6-acre plot to the east of the current housing on the farm, which is slanted at a 17-degree angle above the horizontal. Because the hill is south-facing, our agrivoltaic design for this site placed crops on the East-West axis, allowing rows to be terraced to aid in picking. Rows of solar collectors representing strawberry and lettuce crops were modeled as 26 ft long and 1 ft wide. Single-axis tracking panels were racked in a north-south orientation to capture the maximum amount of sun throughout the day, while taking advantage of the sloped hill to further improve production. Fixed-tilt panels were racked from east to west, tilted at a 45-degree angle to optimize production. Both the spacing between panel rows and the height of the panels were varied for the fixed-tilt panel models. Table 5 contains the specifications for 10 agrivoltaic designs for Centralia 43. To understand the impact of panel orientation and type (fixed vs. tracking), interrow panel spacing (pitch) and panel height on crop shading, we generated combinations of fixed tilt tracking arrays that varied row spacing (low, medium high) and panel height (4, 6, 8 feet above ground) and a single-axis tracking system at 6 feet above ground with low spacing.

Figure 18. Centralia 43's agrivoltaic design using fixed tilt arrays with 12.3 ft spacing between rows (top). Agrivoltaic design using single axis tracking arrays with 9.8 ft spacing between rows (bottom). Rows of crops are underlaid.

Crop shading results showed that single-axis tracking arrays resulted in highest levels of shading (69%), followed by a conventional fixed tilt array (4ft high, 12.3 ft pitch) (Table 6). Amongst fixed tilt arrays, increasing interrow panel spacing (pitch) by 2 feet increased light availability by 11-12% on average, whereas increasing panel height by 2 feet increased light availability by 5-6% on average (Table 6, Figure 19). Blueberries in low solar radiation intensity growing regions show yield benefits up to 30-35% shading, beyond which yield would begin to decline (Hermelink et al 2024 Laub et al. 2022; Appendix Figure 29). The following fixed tilt designs would achieve 33-37% shading: 8 ft with 14.3 ft spacing, 4ft with 16.3 ft spacing, 6ft with 16.3 ft spacing, 8ft with 16.3 ft spacing. Tracking arrays at the pitch we modeled will likely be detrimental to berry production, although we did not explore higher pitches (lower spacing) to determine the optimal spacing for tracking arrays.

Using the shading profiles (Figure 19), we modeled lettuce and strawberry crop yield impacts of each agrivoltaic array design (Figure 21). Results indicate that strawberries will experience 30-45% yield declines due to shading in fixed tilt arrays and a 64% decline in yield in a single-axis tracking array elevated to 6 feet (Figure 21). These results are consistent with metanalyses of empirical studies of shading on strawberry yield (Hermelink et al. 2024; Appendix Figure 29). Lettuce yield reduction is far less significant compared to strawberries, with 9.3-14% annual yield reductions for fixed tilt arrays and 17.7% reduction for tracking arrays. Seasonal variation in lettuce shading impacts shows that the greatest negative impacts occur in the fall, when the sun is lower on the horizon and at an angle that maximizes shading on crops planted below and north/behind the panels.

Photovoltaic energy simulation results show that the tracking array would yield the highest electricity generation, as expected, and that it would also result in the lowest levelized cost of electricity (Figure 20), due to the much higher capacity factor (Figure 20) despite the higher capital costs (Figure 20). For fixed tilt arrays, the most cost-effective system is medium spacing (14.3 ft) at 4 ft height, since it reduces inter-panel shading enough to compensate for the additional cost of electrical equipment needed for more widely spaced panel rows (Figure 20). Given the desire to maintain shading in the 30-35% range, the fixed tilt with 6 ft height and 16.3 ft spacing or fixed tilt with 8 ft and 14.3 ft spacing array designs would be the lowest cost ($85-86/MWh) blueberry-appropriate designs. There is significant geographic variation in the LCOE for utility scale solar projects in the US (Appendix Figure 28), but $85/MWh would put the Centralia 43 agrivoltaic system in the middle to upper range of solar projects sited in MISO (Midcontinent Independent System Operator), PJM (Pennsylvania-New Jersey-Maryland), ISO-NE (Northeast), and NYISO (New York) (Appendix Figure 28).

Table 5. Design specifications and modeled energy production for Centralia 43 agrivoltaic arrays

	Fixed tilt - low spacing	**Fixed tilt - medium spacing**	**Fixed tilt - high spacing**	**Single-axis tracking**
Panel row orientation	east-west	east-west	east-west	north-south
DC Capacity (MW)	1.697	1.436	1.436	1.942
Area (acres)	5.34	5.05	5.56	5.56
Panel row pacing or pitch (ft)	12.3	14.3	16.3	9.84
Row lengths (ft)	52.5 (2 rows side by side)	52.5 (2 rows side by side)	52.5 (2 rows side by side)	70.5
Number of rows	288 (2 rows side by side)	240 (2 rows side by side)	240 (2 rows side by side)	288
MWh/year	2,116	1,800	1,805	2,764
Height(s) (ft)	4, 6, 8	4, 6, 8	4, 6, 8	6

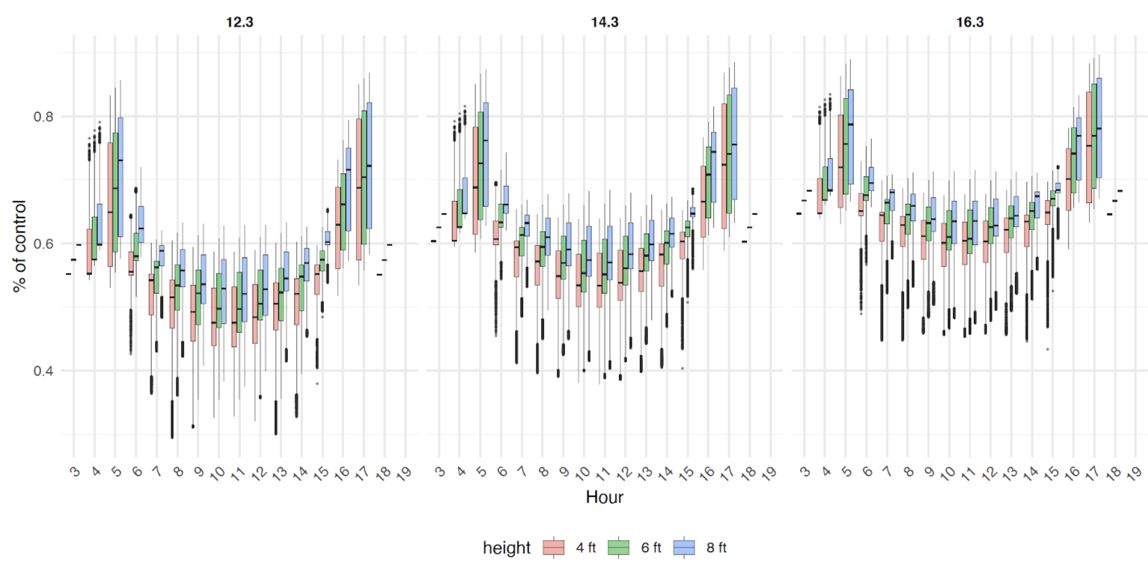


Figure 19. Solar radiation (W/m2) available to crops expressed as percent of control radiation (no solar panels) for three panel row spacings (12.3 ft, 14.3 ft, 16.3 ft) and for three panel heights (4, 6, 8 ft) at Centralia 43 Farm. Data are from 11 years of hourly simulations (2010-2020).

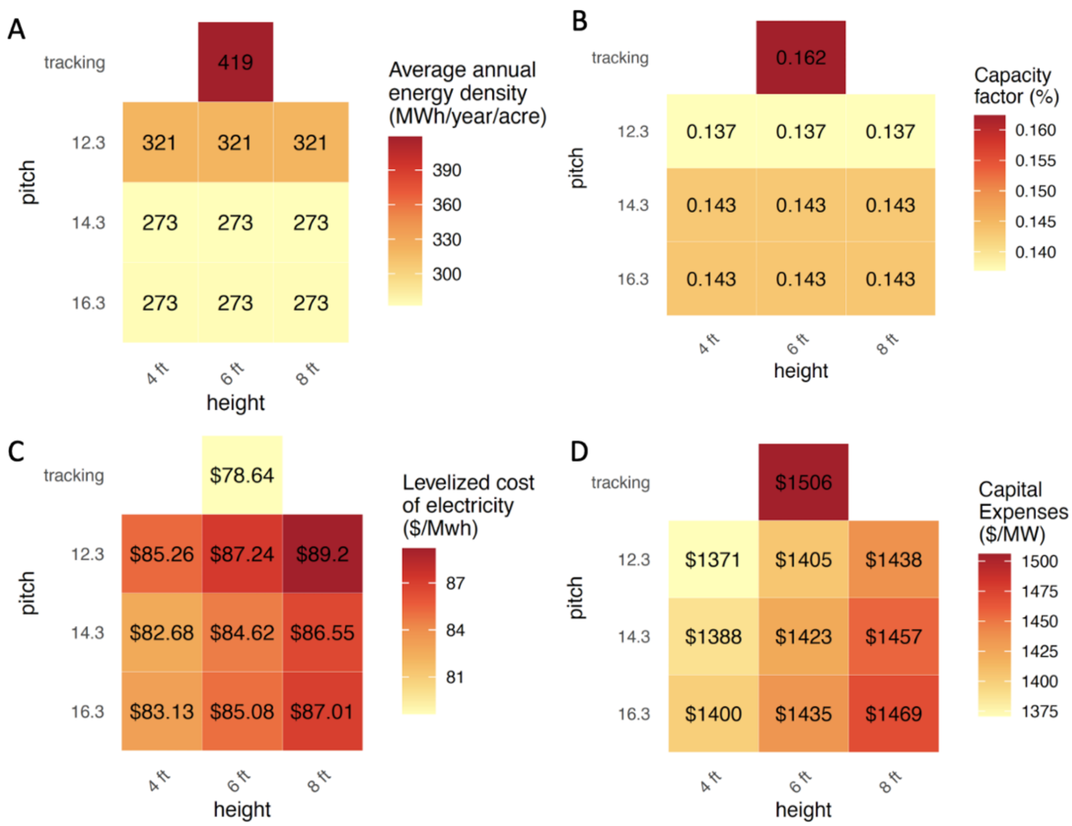


Figure 20. Heatmap of Centralia 43's agrivoltaic electricity generation performance indicators. Electricity production modeling results reporting the average annual energy density (MWh/year/acre) (A), the capacity factor (% of installed DC capacity) (B), the levelized cost of electricity ($/MWh) (C), and the estimate capital expenses ($/MW) (D) for the 10 agrivoltaic array designs. The single axis tracking system is indicated as the "tracking" row for pitch.

In terms of energy density, the tracking system is showing a higher-than-average energy density for projects in locations with similar annual radiation (Centralia's annual average global horizontal irradiance (GHI) is 3.38 kWh/m2/day) . The fixed tilt energy density for the low spacing design is aligned with national trends, but the medium and high spacing reduces the energy density below 300 MWh/year/acre, as expected (Figure 20).

Table 6. Centralia 43 shading (average percent reduction in hourly solar radiation) on crops for each array design

	4 ft above ground	6 ft above ground	8 ft above ground
Single axis tracking	-	68.7%	-
Fixed tilt - 12.3 ft spacing	47.8%	45.1%	42.2%
Fixed tilt -14.3 ft spacing	42.2%	39.7%	37.4%
Fixed tilt - 16.3 ft spacing	37.2%	35.0%	33.3%

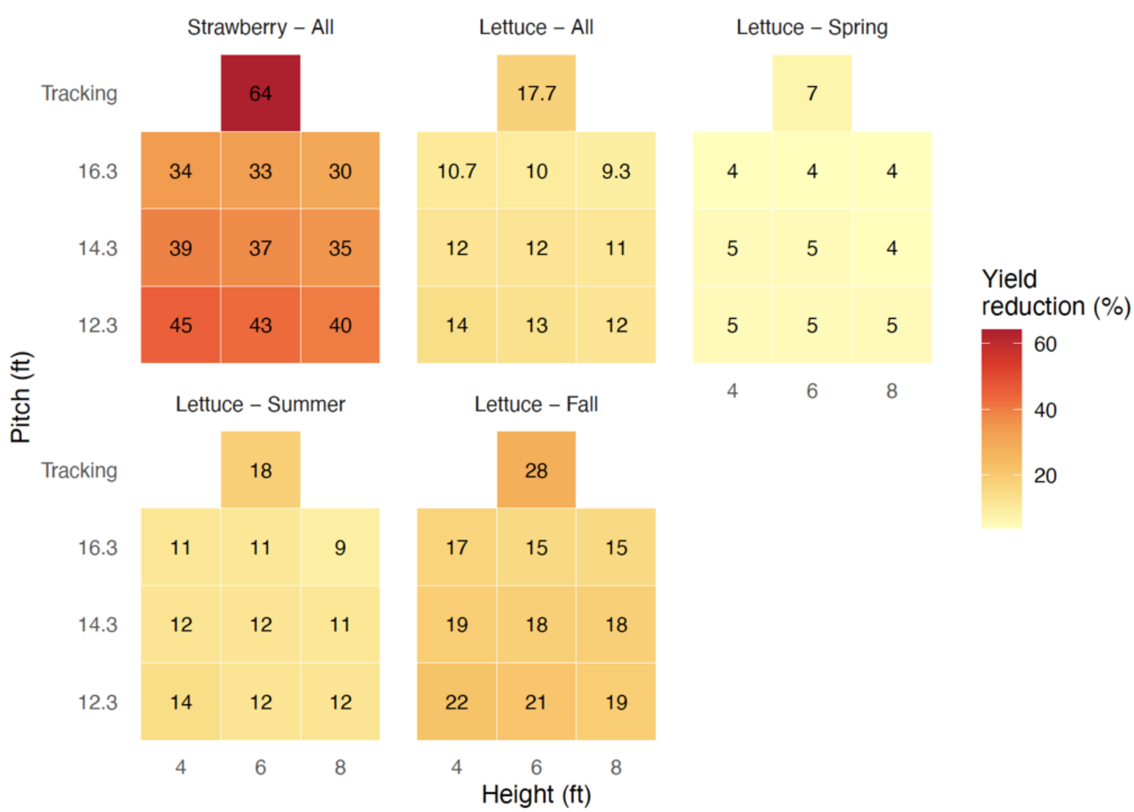


Figure 21. Average annual crop yield impacts of PV panel shading expressed as percentage yield reduction for each agrivoltaic array design (combination of pitch and height for fixed tilt designs and single axis tracking at 6 ft panel height). Strawberries have a single continuous growing season (All), whereas lettuce can be grown in the spring (Mar 1-Apr 22), Summer (May 15-Jul 6), and Fall (Aug 1-Sep 22). Average annual yields across all seasons for lettuce are also reported.

Small Acres

Figure 22. Parcel map of Small Acres farm (pinned) with the approximate location of the designed agrivoltaic system indicated with the yellow box (top). Fixed tilt design for Small Acres with rows of crops directly underneath and north of the panels (bottom).

Small Acres is a farm located in Whatcom County, owned and managed by Mia Devine and Chris Henderson. The farm currently grows a mix of vegetables that are sold directly to market. Mia and Chris are planning to install a small 30 kW fixed-tilt ground-mount system as a single row (yellow box in Figure 22) and are considering growing some crops under and around the panels. Likely crops would be cut flowers (perennial or annual), annual vegetables, or berries. They are also considering raising chickens under and behind the panels, which would provide needed shade during the summer months. Cultivation would mostly be with hand tools and a walk-behind tractor. During discussions with Mia and Chris, summer lettuce and other leafy greens (kale, napa cabbage) stood out as high value crops that would be suitable for agrivoltaics, as leafy vegetable quality is typically lower in the peak summer season due to heat. While Mia and Chris would consider a larger agrivoltaic array, currently, the net energy metering policy caps behind-the-meter projects at 100 kW and compensation rates are such that solar owners are not incentivized to oversize arrays to sell electricity to the utility. Mia and Chris's primary motivation for installing the solar array is to meet increasing onsite electricity needs. Because they already planned to install the 30 kW fixed tilt array, we did not produce multiple designs. Instead, we simply elevated the array to 6 feet (from a typical height of 4 feet), which would allow farm workers to access the area underneath the panels.

The following are the photovoltaic generation performance indicators for a 30 kW, fixed tilt array elevated to 6 ft:

- Average hourly crop shading (hourly percentage shaded averaged across all hours and years): 32.5%
- Total annual crop shading (shading radiation losses summed across all hours across 10 years then divided by unshaded control): 40.1%
- Average annual CF (capacity factor): 14.14%
- Average annual electricity generation: 37.2 MWh
- Levelized cost of electricity: $84.48/MWh

Shading impacts show 32.5-40.1% reduction in solar radiation due to the panels. Most of the reduction occurs in the middle of the day (10 am to 2 pm), with about 63-70% of the incident solar radiation available to crops (or 30-37% shading) (Figure 23). The average annual capacity factor is typical for the amount of solar radiation (3.5 kWh/m2/day) available at the location, as is the LCOE.

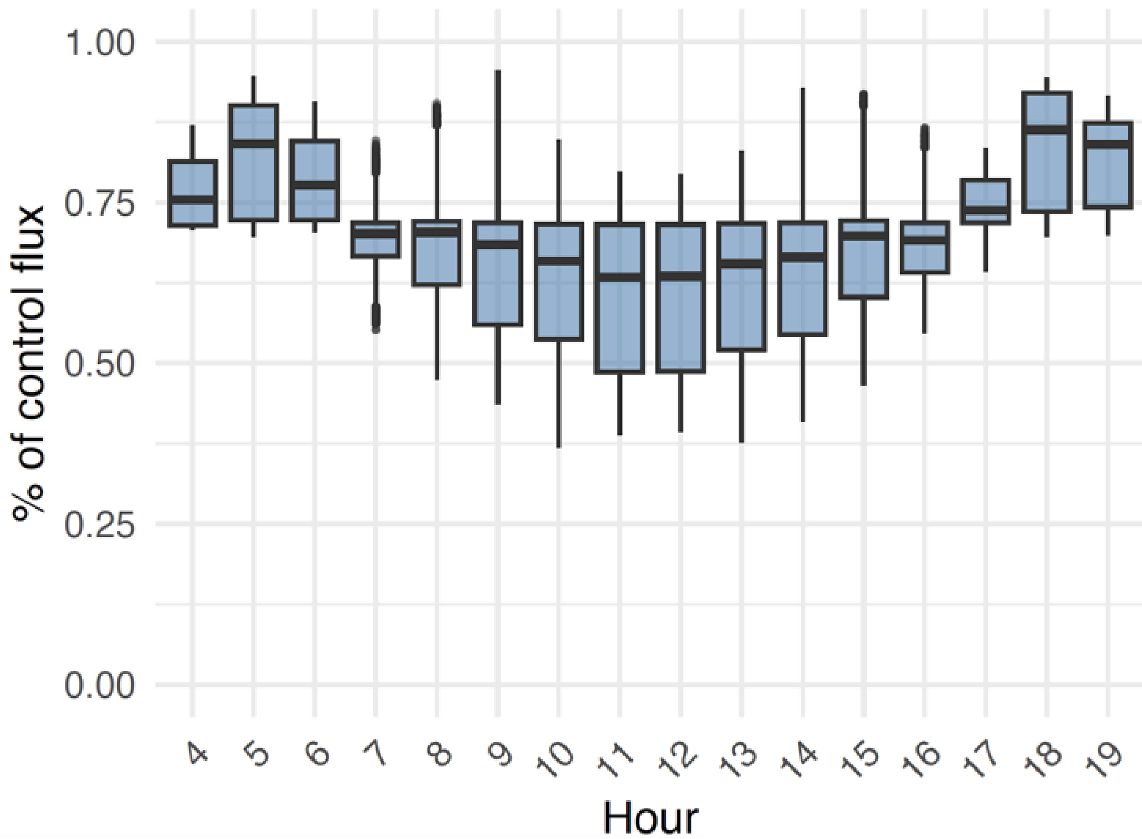


Figure 23. Solar radiation (W/m2) available to crops expressed as the percent of control radiation (no PV panels) across 11 years of simulations (2010-2020) at Small Acres farm.

The following are the simulated crop yields for strawberries and lettuce grown underneath and north of the panels, expressed as a percentage of unshaded yield:

- Strawberry yield impacts: 60% Yield
- Lettuce yield impacts (Mar 1-Apr 22): 100% Yield
- Lettuce yield impacts (May 15-Jul 6): 99% Yield
- Lettuce yield impacts (Aug 1-Sep 22): 95% Yield

Strawberry results are consistent with trends described by (Hermelink et al. 2024) for strawberry yield response to shade in shade cloth studies, which predict about 45-50% yield reduction with 35-40% shade in low-radiation growing regions (Appendix Figure 29). Lettuce results in the fall season are somewhat consistent with previous literature as well (Appendix Figure 30) with lettuce experiencing slight yield reductions beyond 25% or more shading (Laub et al. 2022), though there is still considerable uncertainty about the general yield response of lettuce shading (Weselek et al. 2019). The percentage shading is highest in September (approximately 50%), which is when the sun is at an angle low enough in the sky to shade more plants grown directly north of the panels. This explains why the yield reduction (5%) is largest during the fall cycle.

Stonemetz Orchards

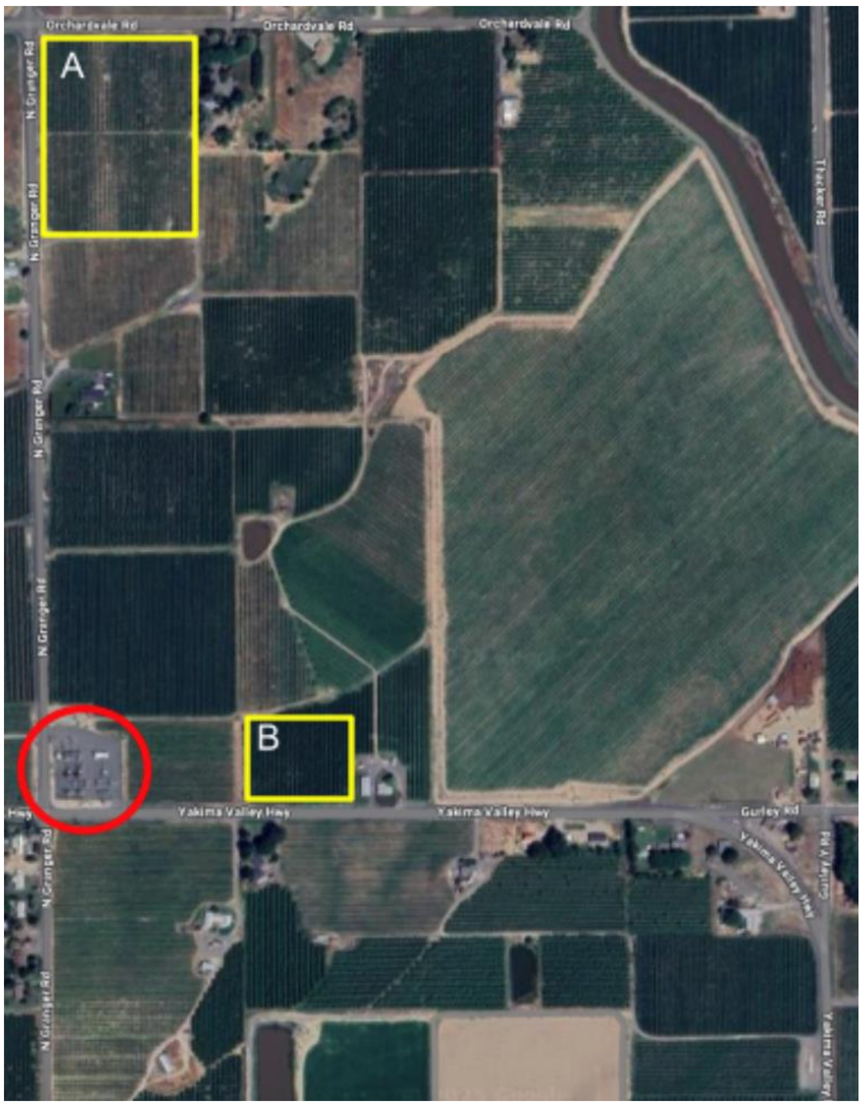


Figure 24. Map of the extent of Stonemetz Orchards with the approximate locations (A and B) of the designed agrivoltaic systems indicated with the yellow boxes and the location of a substation indicated with the red circle.

Stonemetz Orchards is a 110-acre apple and cherry orchard located in Yakima County, owned and managed by Shane Stonemetz. Because Shane's parcels are located around a large substation, Shane has received mailed inquiries from solar developers, and he has expressed interest in solar development on his farm. The apple grower's market has become more competitive, and the costs of production have increased due to higher water expenses and the need for shade cloth, frost, and hail protection. Small and medium scale orchardists are increasingly being pushed out of the dessert apple market and into the lower value cider and slicer markets because of the additional expenses related to maintaining fruit quality. Shane, like many other farmers, are interested in solar as a supplementary and more reliable income stream. He expressed a willingness to experiment with fruit quality and yield and requested a 5-8 acre agrivoltaic system design.

After visiting the farm, we selected two parcels for the agrivoltaics array design–Parcel B is a cherry orchard with north-south oriented rows and Parcel A is an apple orchard, also with north-south oriented rows (Figure 24). While several of Shane's parcels south of Yakima Valley Hwy are closer to the substation, those rows are oriented east-west, which would make them less suitable for single axis tracking systems if the panels needed to be arranged directly above the trellised rows of trees. Short narrow tractors and 8 ft wide mowers are the only machinery used on the farm, which is typical for most orchards. This further suggests that PV panels and their support structures would ideally be confined to above the rows, with posts (driven piers) in line with the rows. Two of the three variants we designed are single-axis tracking PV arrays that are racked 13 feet above ground, providing 2-3 ft of clearance from the top of the apple canopy, and spaced 10 t apart, directly above the rows. The third variant is a fixed tilt PV array tilted 45 deg south, with rows of panels on a racked structure perpendicular to the north-south oriented rows. Fixed tilt systems are less expensive and the fixed orientation would lead to a markedly different daytime shading profile compared to tracking systems. See Figure 25 for visualizations of these three arrays on Parcel A.

Table 7. Design specifications for Stonemetz Orchards

	Tracking - low density	Tracking - high density	Fixed tilt - low density
DC Capacity (MW)	1.52	2.39	1.52
Area (acres)	6.52	6.52	6.52
# of PV Rows	640	640	240
Length of PV Rows (ft)	41	39	66
Total shading (% shaded)	44.5	63.8	37.2

Energy performance indicators (Table 8) show that Stonemetz Orchard is in an ideal location for solar generation in Washington (compare with other locations for orchards in Figures 29 and 30). Of the three array designs, while single axis tracking low density has the highest capacity factor (capacity utilization factor), it also has the highest cost because there are fewer panels being supported by the same structural supports (poles and tubes) compared to single-axis tracking high density. The fixed tilt low density array has the lowest average annual generation and the lowest capacity factor. The single-axis tracking high density array has 57% more capacity than the other two designs and thus has much higher energy density (610 MWh/acre/year). However, due to inter-panel shading, the capacity factor is lower than the low density tracking design. Because of a higher generation capacity to per unit of support structures ratio, the single axis high density has the lowest levelized cost of electricity (Table 8).

Figure 25. Stonemetz Orchards - agrivoltaic array designs using single-axis tracking arrays at low density (top), single axis tracking arrays at high density (middle), and fixed tilt at low density (bottom). Rows of trellised apple trees follow the orientation and spacing in the orchard.

Shading impacts show 37-64% total shading over the 10 year timeframe of the simulation, with the fixed tilt system resulting in the least shading (37%) and the tracking high density system resulting in the most shading (64%) (Table 7). The daily shading profiles differ significantly between tracking and fixed tilt array designs (Figure 26), with the tracking arrays providing the most shading in the morning, late afternoon, and in the middle of the day (11-12), following a w-shaped pattern. The fixed tilt array shades increasingly over the course of the day, peaking at noon, and then reducing again in the evening, following a v-shaped pattern. This v-shaped pattern provides better protection from high radiation hours that cause apple sunburn, as evidenced by the sunburn risk results (Figure 27). Even though the fixed tilt array resulted in the lowest amount of total shading on the apple trees (37%), this array resulted in a complete elimination (100% reduction) of apple sunburn risk (Table 6, Figure 27), even in the highest wind speed reduction (35%

reduction) scenario. The high density tracking array also showed no sunburn risk at 10% wind speed reduction, but a 95% reduction in sunburn risk at 30% wind speed reduction (Table 6). The tracking low-density design showed a 49-50% reduction in sunburn risk, which while lower than the tracking high density and fixed tilt low density, is better than the 15-25% sunburn risk reduction provided by shade cloth on Honey Crisp apples (Mupambi et al. 2019). While it appears that the fixed tilt array provides the best sun protection while maintaining a relatively high level of solar radiation throughout the year, the percent shading reported in Figure 26 is an averaging across all rows of trees. Some trees will experience higher and more consistent shading than others with a fixed tilt array, which could still result in sunburn (Figure 28). The ideal array design would be a low density tracking system that tracks panels to yield a v-shaped shading pattern, providing consistent shading across all trees during the hottest hours of the day.

Table 8. Stonemetz Orchards electricity output, and crop yields

	Energy performance indicators				**Apple quality performance indicators: Annual average apple sunburn risk reduction (% reduction in number of days a year)**	
	Average annual solar generation (MWh/year)	**Energy density (MWh/acre)**	**Capacity factor**	**Levelized cost of electricity ($/MWh)**	**With 10% wind speed reduction**	**With 35% wind speed reduction**
Single axis tracking - low density	2,755	421	20.5%	78.30	43%	59%
Single axis tracking - high density	3,995	610	18.9%	75.38	100% (no sunburn days)	95%
Fixed tilt - low density	2,305	419	17.2%	77.47	100% (no sunburn days)	100% (no sunburn days)

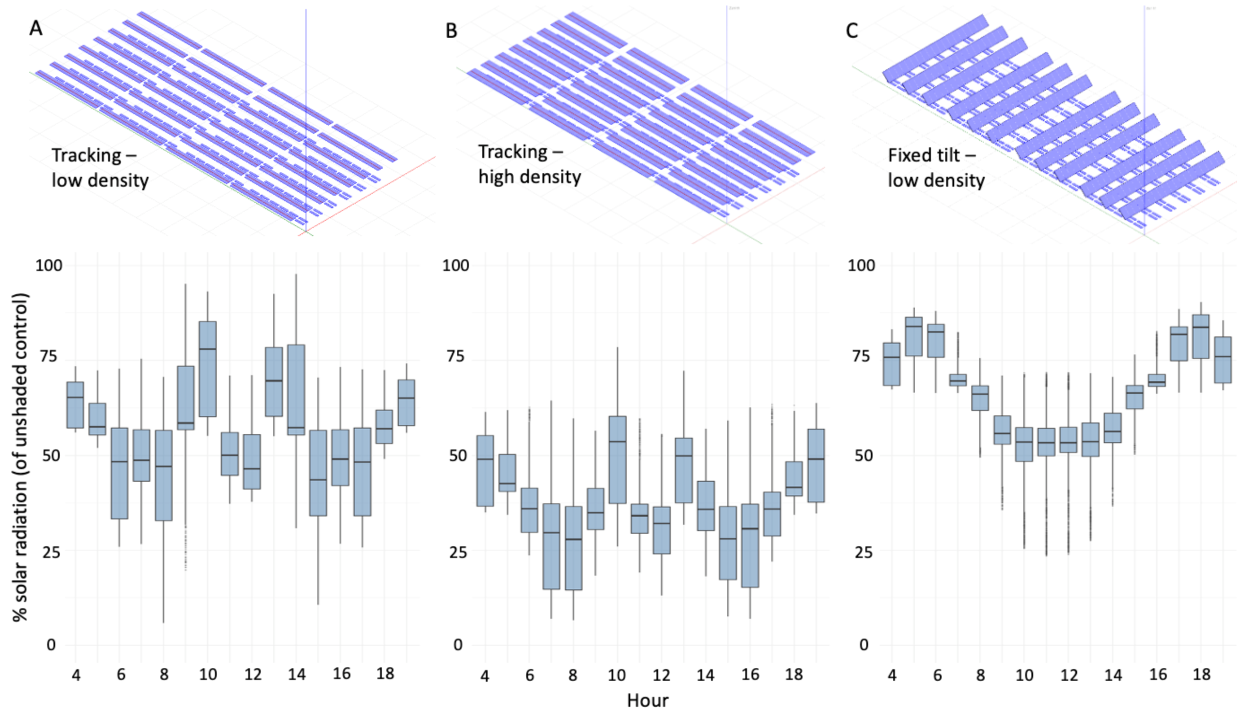


Figure 26. Simulated solar radiation in the rows directly underneath the PV panels, expressed as percentage of the unshaded solar radiation for the Stonemetz Orchard agrivoltaic parcels. Single-axis tracking arrays at low density (A), single axis tracking arrays at high density (B), and fixed tilt at low density (C).

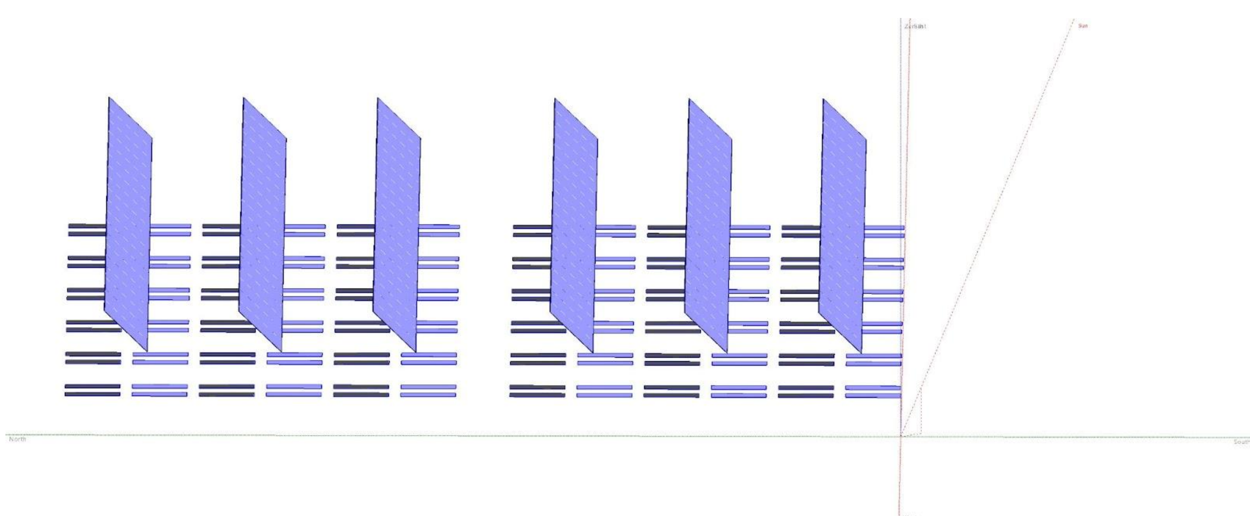


Figure 27. Differential shading across rows in a fixed tilt design at 10 am on July 1st, 2022. Shaded orchard rows are indicated in dark purple. Viewing orientation is from the west. Rows are north-south oriented and PV panels are east west oriented.

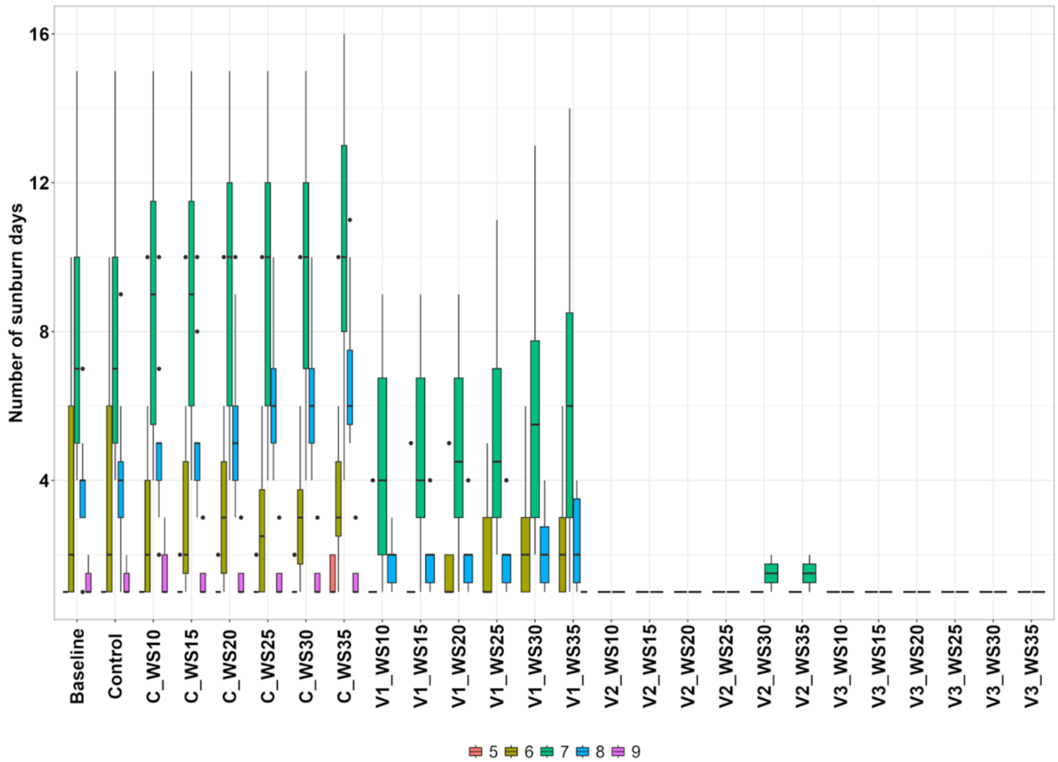


Figure 28. Stonemetz orchard differences in apple sunburn risk across agrivoltaic array designs. Apple sunburn days by month (5 = May, 6 = June, 7 = July, 8 = August, 9 = September) for control (no solar panels) (indicated with C), single-axis tracking arrays at low density (V1), single axis tracking arrays at high density (V2), and fixed tilt at low density (V3). Each design and control also includes a set of sensitivity results that incrementally reduce the wind speed (WS) by 5%. For example, C_WS35 is the result for the control at 35% wind speed reduction. The boxes represent the distribution of sunburn days across 10 years of simulations (2013-2022).

Statewide Apple Orchard Agrivoltaic Performance and Apple Sunburn

To understand how electricity generation, levelized cost, and apple sunburn risk of different agrivoltaic array designs varies geographically—and specifically whether certain locations would be most amenable for agrivoltaic apple orchards—we simulated the photovoltaic performance and sunburn risk of several agrivoltaic designs across 10 representative dessert apple growing regions in Washington.

Energy density: Results for energy density, or the amount of annual electricity generation per unit land area, follow a clear latitudinal trend, tracking the increase in solar radiation from north to south (Figure 29). Despite being designed to have lower panel density per panel row—but simultaneously constrained by the tree row spacing of 10 feet—energy density values for tracking low density and fixed tilt low density fall within or just below the predicted values based on other utility-scale solar projects in the US with comparable GHI (global horizontal irradiance). Tracking high density designs, on the other hand, are well above and nearly double (560 - 630 MWh/year/acre) the expected energy density values based on other tracking projects (310-350 MWh/year/acre) of comparable GHI (Figure 29). This is likely due to the low interrow panel spacing, which was a design specification determined directly by the 10 feet of interrow (trellised) tree spacing which is a common spacing choice across most trellised orchard layouts.

Economics of the photovoltaic system: The higher density tracking array design does result in higher inter-panel shading, which reduces the capacity factor. However, because the higher density tracking array supports more panels per elevated row, the cost savings from more efficient use of the same structural support resulted in lower levelized cost of electricity (LCOE) estimates (Figure 30). However, the median LCOE for tracking low density is only about 1.6% higher and the median LCOE for fixed tilt low density is about 4% higher than tracking high density arrays (Figure 30). Across the state, the most cost competitive apple orchard agrivoltaic systems are found in Yakima County, followed by orchards on the border between Douglas and Chelan Counties, and then those in Grant County. LCOE values in the $70 - $75/MWh range is well within the range of values observed for solar projects in the US, and below the mean compared to ISO-NE (Northeast Independent System Operator), and NYISO (New York) (Appendix Figure 28; Seel et al. 2024). Even the highest cost modeled orchard agrivoltaic projects in Washington state, located in the northern Okanogan County, is around $82-$85/MWh, which is on the upper end of utility-scale solar projects, but still close to the median LCOE observed for solar projects at higher latitude Independent System Operators (ISOs). These estimated LCOE ranges are about one-third to one-half the cost of residential rooftop solar projects, and on the lower end of community solar, commercial and industrial solar projects ($81 to $217/MWh; Lazard 2025). **In summary, while orchard agrivoltaic projects in Washington will be higher cost than a standard ground-mount utility-scale project, the costs are still within the range of utility-scale solar projects nationally and comparable with LCOEs of solar projects in regions at similar latitudes and solar radiation (Appendix Figure 28). The most cost-effective orchard agrivoltaic systems will be located in central Washington (e.g., Yakima, Benton, Grant, Chelan counties).**

Shading impacts and sunburn days: Average hourly percent reduction in solar radiation on the trees is 45% for Tracking low density, 64% for Tracking high density, and 37% for Fixed Tilt low density. Diurnal shading patterns across the year differ significantly between tracking and fixed tilt array designs (Figure 26 for Stonemetz Orchard and Figure 31 for aggregate across all 10 sites). As described in the case study for Stonemetz Orchard, the tracking arrays provide the most shading in the morning, late afternoon, and in the middle of the day (11 am to 12 pm), following a w-shaped pattern over the course of the day (Figure 31). The fixed tilt array results in a v-shaped diurnal shading pattern, wherein shading intensity increases over the course of the morning, peaking at noon, and then reduces again over the course of the afternoon.

To understand how these shading profiles impact apple quality and compare with shade cloth as a sunburn mitigation strategy, we estimated the number of sunburn hours for Honey Crisp apples grown under each agrivoltaic array design using an empirical model. Like the apple sunburn risk results for Stonemetz Orchard, this v-shaped pattern provides better protection from high radiation hours that cause apple sunburn (Figure 22). The tracking low density array reduces median sunburn days across all 10 sites by 60%, assuming a 10% wind speed reduction, or 40% if we assume a 35% wind speed reduction due to the presence of the elevated PV panels (Figure 32). The tracking high density and fixed tilt low density arrays result in a 93-95% and 87-91% reduction in the average number of sunburn days across all sites, respectively, with the range representing the uncertainty in wind speed reduction. Tracking high density and fixed tilt low density have similar reduction in average sunburn days, but the benefits will not be uniform across all trees in the fixed tilt array—with some apples getting more solar radiation and others less, with the average effect being the percentage reported—as explained in the Stonemetz Orchard case study. Sunburn risk was modeled using the NSRDB wind speeds, which are on average lower than the GridMET wind speeds the apple fruit surface model was calibrated to. Thus, these results may slightly overestimate the absolute number of sunburn days, but the high wind speed reduction sensitivity scenarios provide a sense of the changes that would result due to use of systematically lower wind speeds than measured.

The reduction in sunburn days due to PV panel shading differs geographically across the dessert apple growing region (Figure 33 and Figure 34). Orchards in the Grant, Franklin, Benton, Walla Walla, and part of Yakima counties see reductions of 80-85% for Tracking high density and Fixed tilt low density designs and

34-47% for Tracking low density designs. In contrast, all other growing regions experience a 92-96% decline for Tracking high density and Fixed tilt low density designs and 62-69% reduction for Tracking – low-density designs. **This suggests that all three agrivoltaic designs can reduce Honeycrisp sunburn risk well beyond the 20-25% reduction provided by shade cloths (Mupambi et al. 2019). However, the low-density arrays provide mean annual shading of 42-44%, which exceeds the 19-25% shading from shade cloth and is likely to reduce yields while increasing the percentage of marketable fruit.**

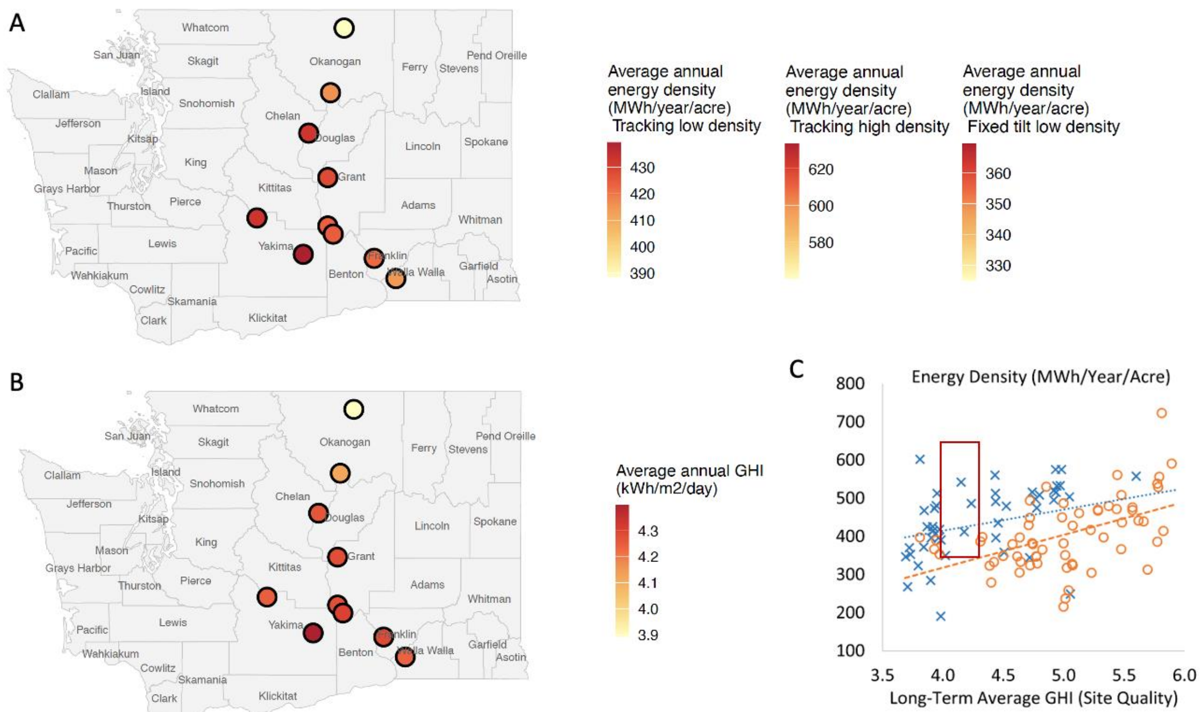


Figure 29. Energy density of apple orchard agrivoltaics systems. (A) Energy density of three different apple orchard agrivoltaic array designs across the state. (C) Energy density of utility-scale solar projects in the United States as a function of average GHI in kWh/m2/day (reproduced from (Bolinger and Bolinger 2022)). Orange open circles indicate tracking systems and blue x's indicate fixed tilt systems. Using the average annual GHI of each site (B), the range of agrivoltaic energy density and GHI values observed for the 10 sites is indicated with the red box in Panel C.

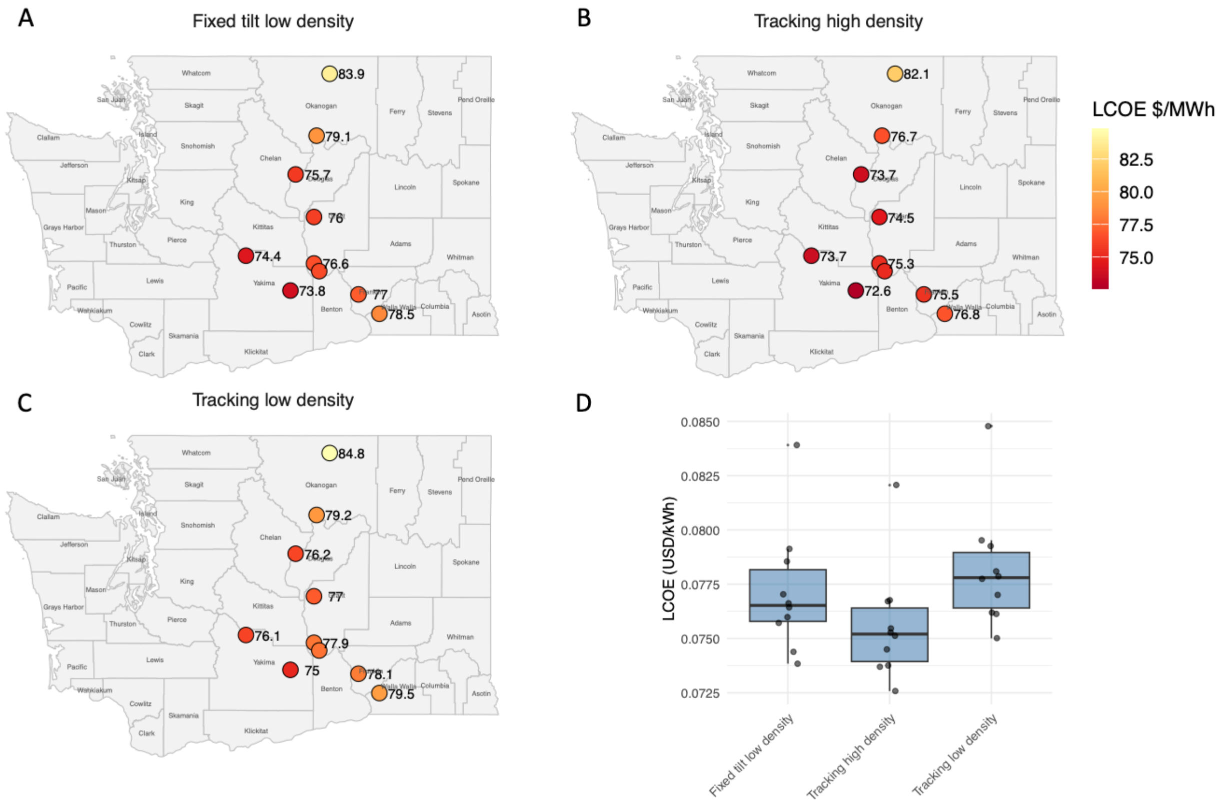


Figure 30. Levelized cost of electricity (LCOE) of apple orchard agrivoltaic array designs. Maps show the distribution of average LCOE across the state (A, B, C) in USD per MWh. Box plots show the differences between designs, aggregating across locations (D).

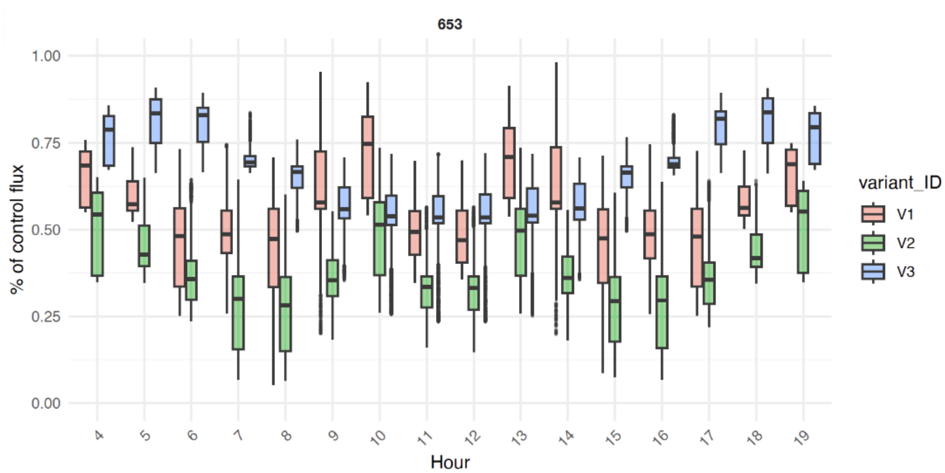


Figure 31. Solar radiation available to trees underneath the PV panels, expressed as percentage of the unshaded solar radiation for the three variants: Tracking low density (V1), Tracking high density (V2), and Fixed tilt low density (V3). The box plots show distribution of shaded radiation for one example locations and 10 years of simulations (2013-2022).

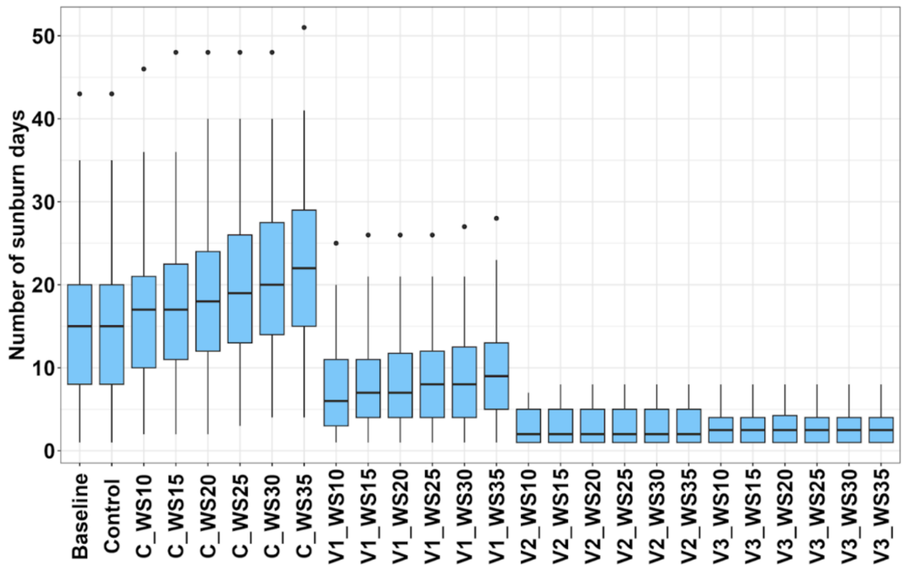


Figure 32. Distribution of apple sunburn days across 10 representative orchard locations in Washington for each agrivoltaic array design. Annual average apple sunburn days for single-axis tracking arrays at low density (V1), single axis tracking arrays at high density (V2), and fixed tilt at low density (V3). Each design and control also includes a set of sensitivity results that incrementally reduce the wind speed (WS) by 5%. For example, V1_WS35 is the result for the tracking low density array at 35% wind speed reduction. The boxes represent the distribution of sunburn days across 10 years of simulations (2013-2022) across all 10 locations.

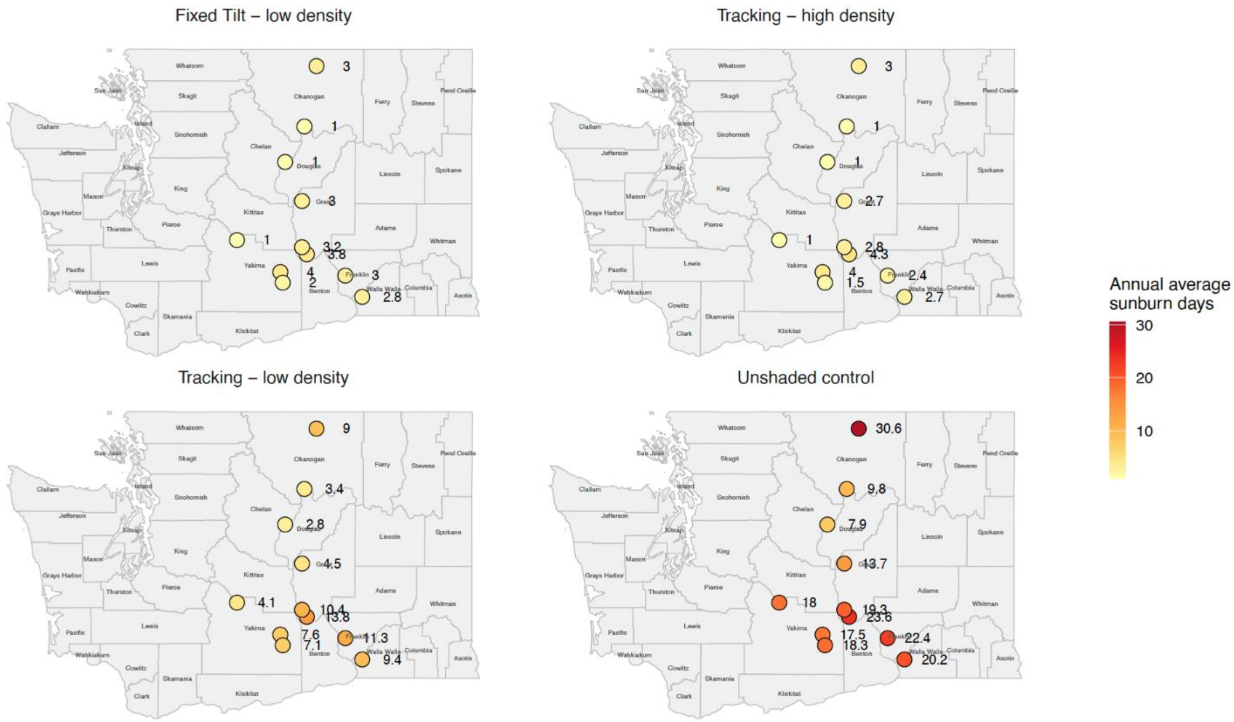


Figure 33. Representative site-specific annual average sunburn days for each of the three agrivoltaic array designs and the unshaded control.

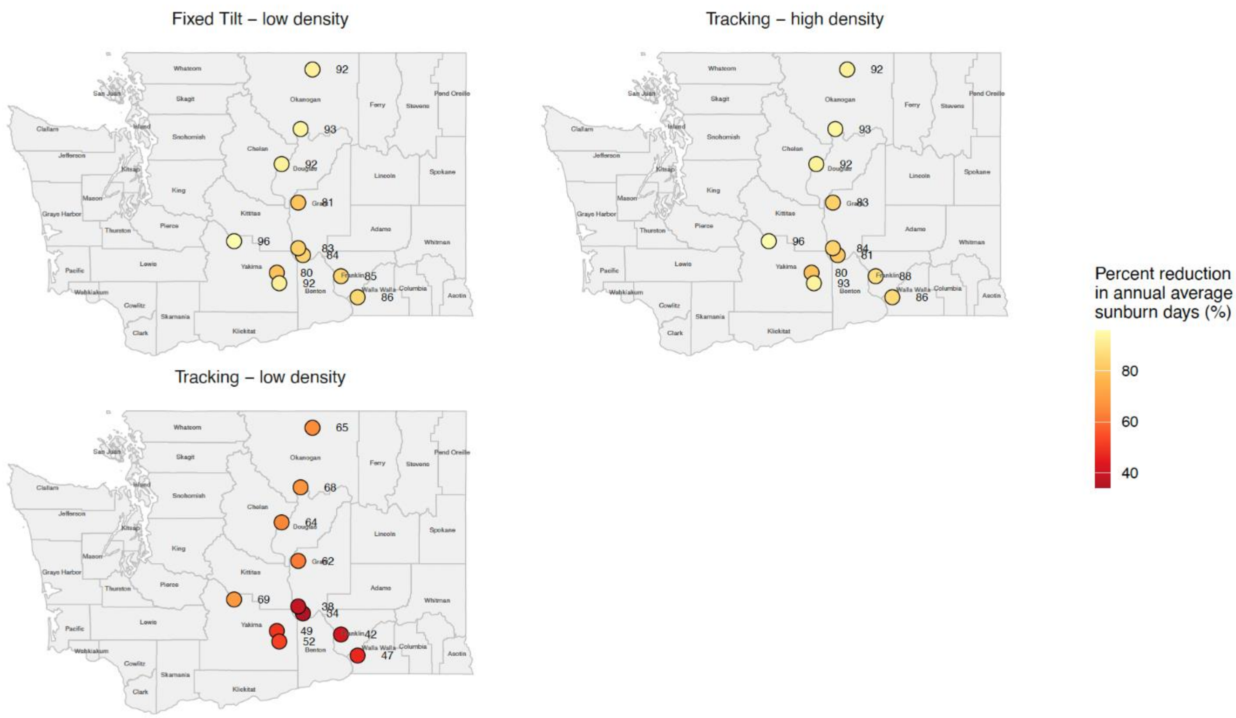


Figure 34. Representative site-specific percent reduction in annual average sunburn days for each agrivoltaic array design assuming a 20% windspeed reduction compared to the unshaded control using unmodified windspeeds.

Berry and Vegetable Agrivoltaic Systems

To quantify the impact of agrivoltaics on electricity generation, levelized cost, and crop yields across the state, we modeled the performance of the photovoltaic system and lettuce and strawberry yield impacts of multiple agrivoltaic array designs across 15 representative berry and vegetable growing regions in Washington.

Energy density and economics of the photovoltaic system: Three levels of increasing pitch (spacing between panel rows) were studied to compare the energy density and shading effects at each spacing, as well as a full density tracking array. Energy density (MWh/acre/year) is higher in central and eastern Washington than in western Washington (Figure 35). The energy density ranges from 247-280 MWh/acre/year in western Washington to 311- 337 MWh/acre/year in central/eastern Washington for the lowest density fixed tilt system (16.3 ft pitch). The latter is on the very low end of energy density values for fixed tilt systems in comparable solar radiation regions nationally. The capacity factor for each array design increased with increasing pitch. As the fixed tilt panels were spaced farther apart, there was less inter-panel shading on the middle and rear arrays, resulting in a higher percent yield (Appendix Figure 31). The levelized cost of electricity (LCOE for tracking systems are the most competitive, with $66-$71/MWh in eastern/central Washington and $83-$90/MWh in western Washington (Figure 36). The most economic fixed tilt designs cost $70-$72/MWh, in Yakima County for pitches of 14.3 or 16.3 ft. The highest elevated and most widely spaced fixed tilt design would cost about $71-$77/MWh in eastern/central Washington and $88-$96/MWh in western Washington. Similar to the discussion for apple agrivoltaic LCOEs, the lower end of these ranges for berries and vegetable agrivoltaic designs are comparable to LCOEs of utility-scale solar projects sited at similar latitudes in the US, and the upper end of this range is comparable to community solar, commercial and industry rooftop solar projects sited in places with higher solar radiation.

Yield impacts: The seasonal yields for both strawberries and lettuce were estimated for the fixed tilt tracking array at 16.3 ft pitch and three panel heights (4 ft, 6 ft, and 8 ft) and the single-axis tracking system at 6ft panel height. Strawberry yield was simulated across the entire growing season (Figure 37, Appendix Figure 32) whereas simulations were performed separately for lettuce in the spring, summer, and fall planting and harvest seasons (Figure 38, Appendix Figure 32). Across all sites, the average percentage reduction in strawberry yield is 64% for tracking panels, 33% for 4ft high fixed tilt, 32% for 6ft high fixed tilt, and 30% for 8ft high fixed tilt arrays (Figure 37). The reported yield reduction is similar between all fixed tilt arrays, and the decision on which to build for future agrivoltaic systems is dependent on the site-specific crop value and racking cost. The reduction in cumulative yearly lettuce yield is 14% for tracking panels, 9% for 4 ft high fixed tilt, 8.6% for 6 ft high fixed tilt, and 8% for 8 ft high fixed tilt (Figure 38).

The reduction in yield due to photovoltaic panel shading differs by site. For lettuce, greater reductions in yield is observed in the near the Washington-Oregon border, in Clark, Benton, and Walla Walla counties (Figure 38). For strawberries, central Washington exhibited the highest yield reductions—up to 50% in Douglas County—but are 28-39% in most other parts of the state for fixed tilt designs. The southern growing region also resulted in the most production of strawberries (Appendix Figure 32). The actual production values for these representative sites only offer a point of comparison across Washington's geography, as the actual management parameters and soil used in the STICS model did not vary across each site.

This data suggests that fixed tilt agrivoltaic designs are most suitable for growing strawberries across Washington, and that sites towards Washington's latitudinal center are most impacted by reductions in berry yield due to the increased shading. The data also suggests that lettuce yield is substantially less impacted by increased shading due to agrivoltaics, and that central Washington may be the most geographically suited location for implementation in lettuce farms. Slight changes within fixed tilt designs also appear to have minimal impact in lettuce yield, with very little change in gross yield for different panel racking heights, with 1-2 percentage point improvement in yield with panel mounted higher above ground.

Land Equivalency: The Land Equivalency Ratio, or LER, can be calculated for agrivoltaic systems by summing the percent yield of crops under agrivoltaics, when compared to dedicated farms, and the percent yield of solar energy generation, when compared to full density photovoltaic systems. An LER greater than 1 indicates that the same parcel of agrivoltaics land is being used more efficiently for agrivoltaics than it would be for dedicated farms or photovoltaic arrays. It can be seen that the LER for agrivoltaics systems in berry and vegetable farms is greater than 1 across Washington (Figures 39 and 40). Despite the single-axis tracking array operating at full photovoltaic density, the LER for single-axis tracking over strawberry crops was the lowest of all studied variants. Such a large reduction in crop yield makes it an impractical choice for berry agrivoltaic systems. Nearly all examined lettuce agrivoltaic designs had LER values of over 1.75, with some places showing up to 1.83 for fixed tilt and up to 1.93 for tracking arrays, indicating a 75%-93% increase in land use efficiency with agrivoltaic systems in berry and vegetable farms.

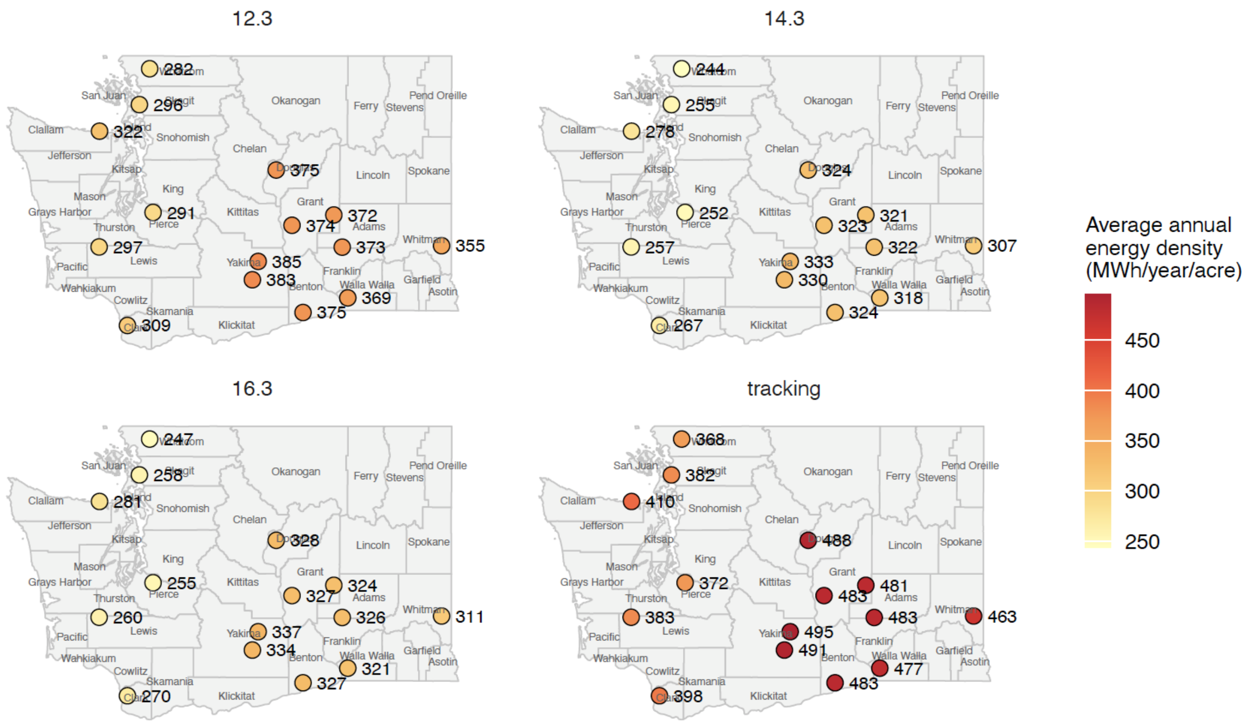


Figure 35. Energy density of berry and vegetable agrivoltaics systems. Energy density for fixed tilt arrays at three pitches (12.3, 14.3, 16.3 feet) and single-axis tracking arrays at representative berry and vegetable locations.

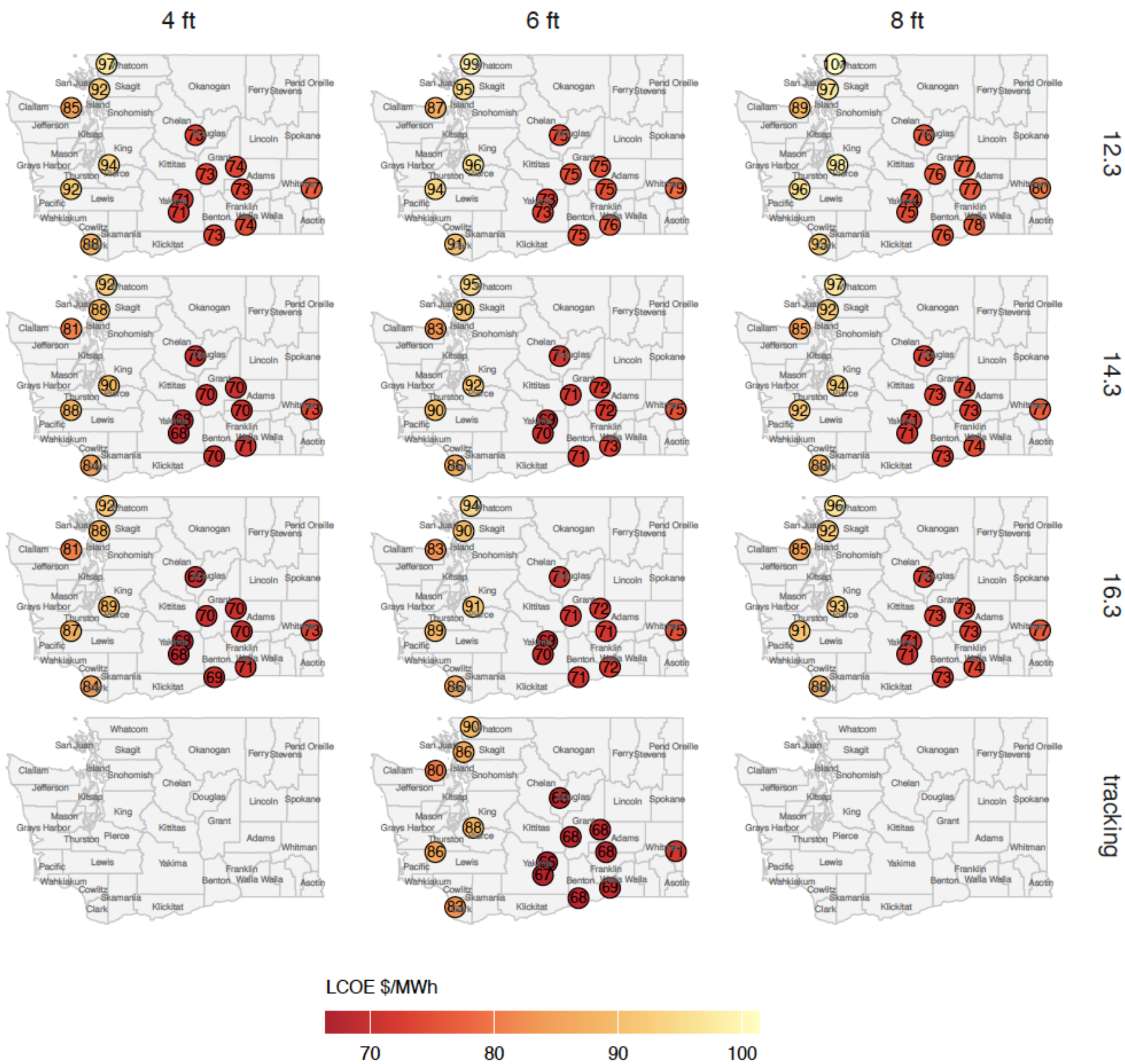


Figure 36. Levelized cost of electricity (LCOE) of berry and vegetable agrivoltaic fixed tilt array designs (pitches vary by row and panel heights vary by column). Maps show the distribution of average LCOE across the state in USD per MWh.

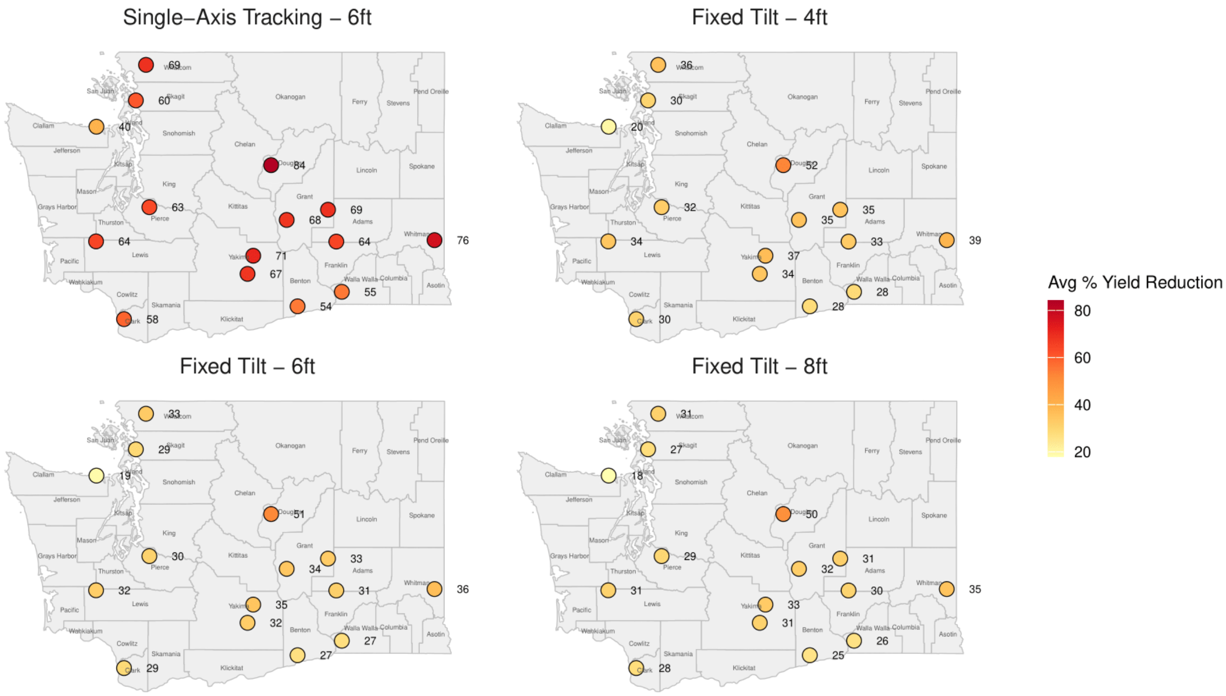


Figure 37. Representative site-specific annual average yield reduction of strawberries for each of the four agrivoltaic array designs.

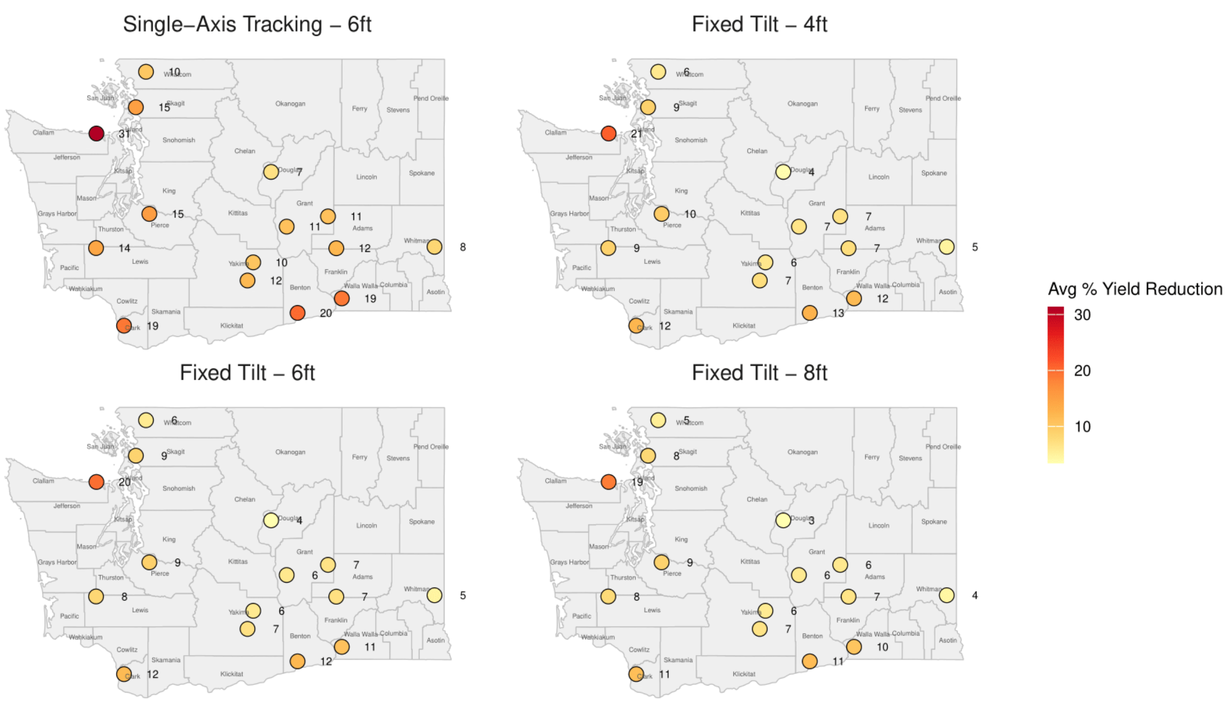


Figure 38. Representative site-specific cumulative average yield reduction of all lettuce cycles for each of the four agrivoltaic array designs.

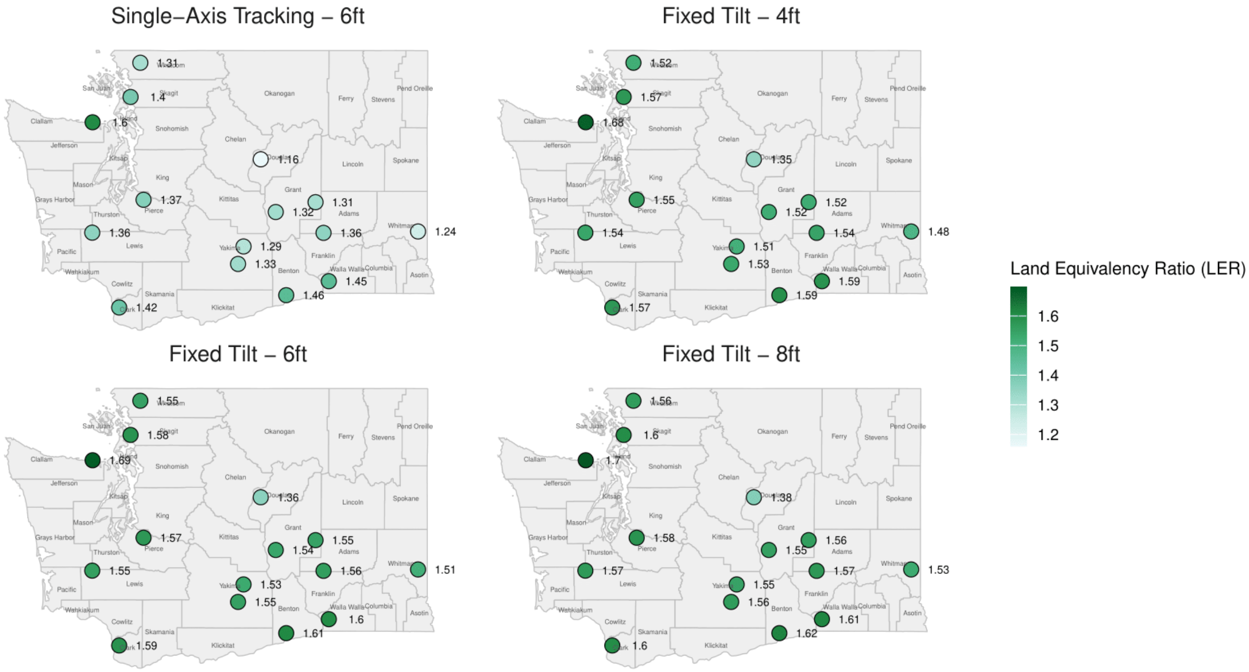


Figure 39. Land Equivalency Ratio for strawberries grown each site. All fixed tilt panels are pitched 16.3 ft apart.

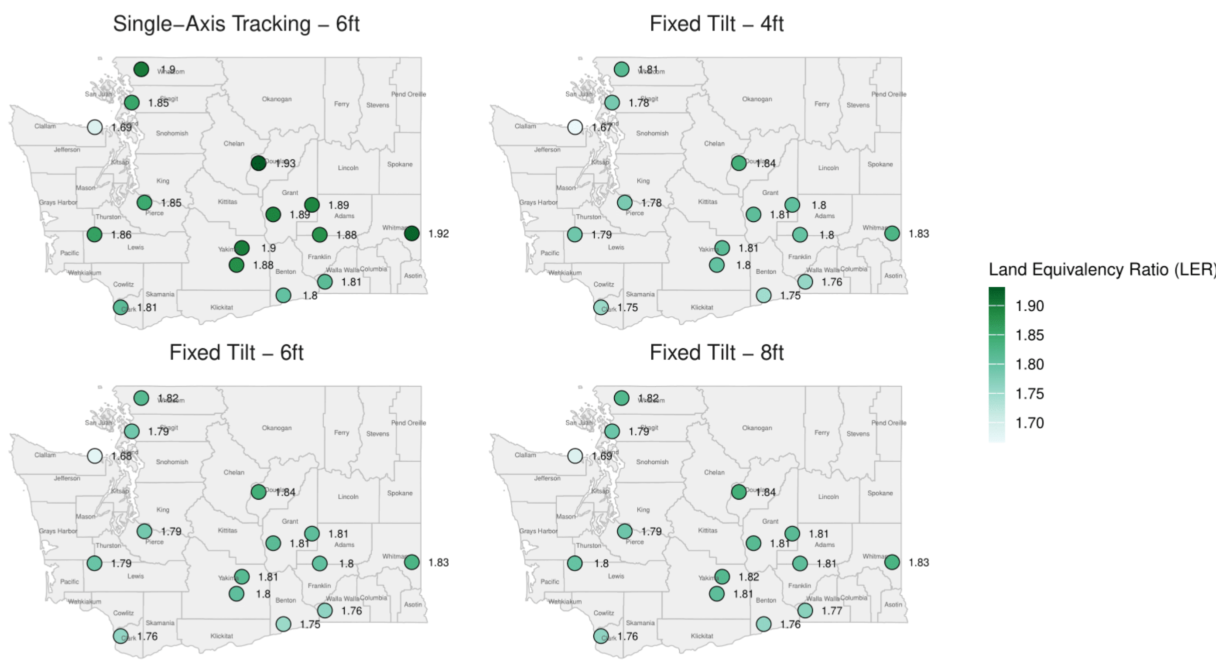


Figure 40. Land Equivalency Ratio for lettuce grown at each site. All fixed tilt panels are pitched 16.3 ft apart.

Conclusions

The economics, land use efficiency, and climate resilience efficacy of crop-based agrivoltaic systems in Washington depend on the array design, crop, and location. Agrivoltaic systems in apple orchards show promise as an apple sunburn mitigation strategy. Results of coupled solar energy and apple sunburn days modeling simulations show that both high and low density single-axis tracking arrays can provide sunburn risk reduction homogenously across rows of apples to levels that exceed those provided by shade cloths. Low density tracking systems result in 45% total annual shading on trellised apple trees, which results in 34% - 69% reduction in sunburn days. The geographic variation in percent sunburn days reduction is only apparent for the low density single axis tracking system, with places that currently experience higher sunburn risk being places that show less risk reduction from agrivoltaics. The high density tracking design is more cost competitive and is estimated to reduce apple sunburn days by 93% - 95%, but this design results in higher shading impacts (greater than 60%), which could negatively impact yields. Apple agrivoltaic systems require elevating panels to 13 feet above ground either through a reinforced regular mount or a racked structure, either of which would result in higher capital costs. We estimate the resulting levelized cost of electricity of apple agrivoltaics systems to range from $70/MWh to $85/MWh, depending on the location and array design, which is on the upper end of all utility-scale PV projects in the US but still significantly lower than rooftop commercial or industrial projects.

Agrivoltaic simulations for lettuce and strawberry production reveal important tradeoffs between yield impacts, array design, and land use efficiency, but show promise for lettuce as an agrivoltaic crop in Washington. Lettuce grown under fixed-tilt systems with greater row spacing (low-density designs) experienced less than 10% average yield reduction across the state, with site-level impacts ranging from 3% to 21%. Interestingly, some locations in western Washington, which is wetter, colder, and has lower solar irradiance, showed yield reductions comparable to central and eastern sites. Standard-density single-axis tracking arrays (with approx. 10 ft inter-row spacing) resulted in slightly higher lettuce yield losses (7–21%) but generated significantly more electricity at a lower cost per MWh. In contrast, strawberries showed much greater sensitivity to shading under tracking systems, with modeled yield losses ranging from 40% to 84% (average 65%), suggesting that low-growing, high-light-demand crops like strawberries may be less compatible with these agrivoltaic designs. Land equivalency ratios (LER) is calculated by summing the ratios of the agrivoltaic system to standard PV project electricity generation and the equivalent ratios of the agrivoltaic and non-agrivoltaic yields. We find that both tracking and tilt lettuce array designs can substantially improve land use efficiency: fixed-tilt and tracking lettuce systems achieve LER values ranging from 1.69 to 1.92—meaning one acre of agrivoltaics provides as much combined food and energy output as 1.7 to nearly 2 acres of single-use systems. Strawberry LER values are lower but still exceed 1.5 on average, indicating potential for co-benefits even with yield tradeoffs.

Farmer Survey

Agricultural communities are key to any potential deployment of agrivoltaics in Washington. As such, understanding farmers' and ranchers' sentiments and perceptions of solar energy, and agrivoltaics specifically, is pivotal. We deployed a survey to farmers combined with targeted interviews to understanding how Washington's farming communities perceive solar energy and agrivoltaics. We began with survey protocols used previously by American Farmland Trust (AFT) in both Colorado and Virginia to assess farmer attitudes toward solar and agrivoltaics. Using existing knowledge of Washington's agricultural context, and with feedback from the project team, AFT customized the survey protocol (see Figure 33) for Washington State. Critically, the survey was designed to ask questions about solar energy in general first and then presented the respondents with images about agrivoltaics and targeted questions about agrivoltaics specifically. This allowed us to begin understanding whether farmers' perceptions towards agrivoltaics was similar or different to other approaches towards solar energy on farmland.

The survey was translated into both Spanish and Hmong, and was distributed primarily via email, directly through AFT's extensive member listserv, as well as those of roughly 60 other agricultural organizations across the state, including Washington Farm Bureau, Washington Tree Fruit Association, and the Washington Dairy Commission. We acknowledge that we were unable to meaningfully engage Tribal communities in this survey. AFT also participated in producer-facing events such as the San Juan Islands Agricultural Summit to raise awareness about the survey. Respondents were incentivized to participate with a chance to win one of twenty-five $100 gift cards.

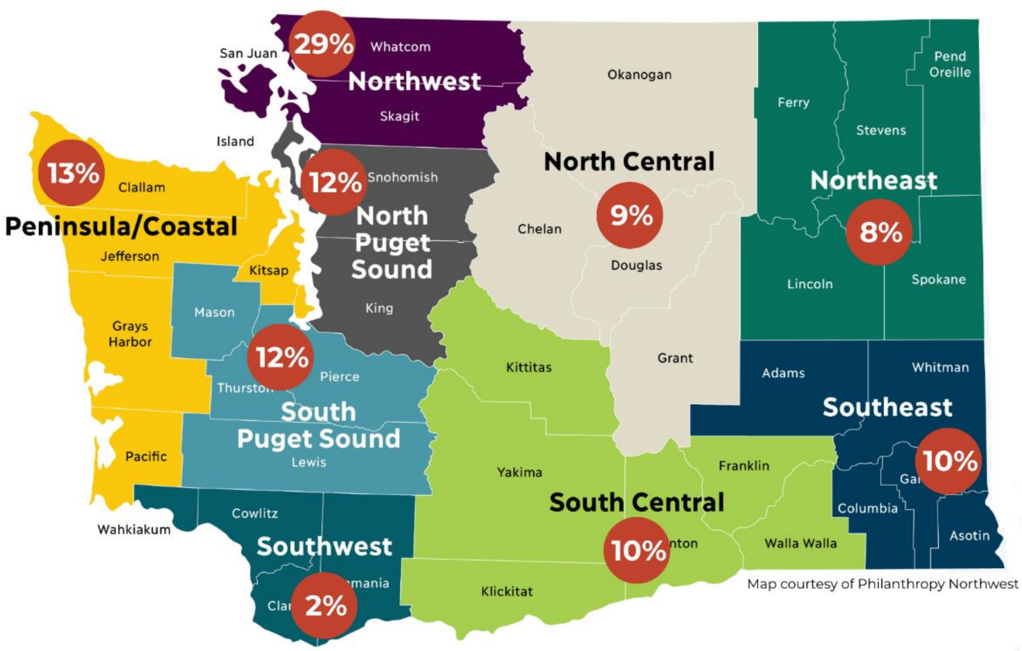


Figure 41. Percentage of high-quality survey responses by geography across 121 survey respondents.

The survey remained open for over eight weeks, from February 25th to April 18th, 2025. During that time, the survey received 834 responses. However, ultimately 713 responses were removed from the analysis as they were incomplete, did not meet survey inclusion criteria (e.g., were not involved in a farm or ranch operation in Washington State), or were flagged for suspected fraud. The data cleaning process resulted in 121 high-quality responses, which were included in the analysis. The 121 responses reflected broad diversity both in terms of geography and agricultural production system (Figure 41).

Over half of survey respondents were based in western Washington, with 56% representing small farms under 50 acres. The majority of respondents (60%) owned all their land, with the remainder renting or a combination of owning and renting.

AFT also developed an interview protocol and conducted in-depth semi-structured interviews with thirteen producers and other stakeholders from the energy development, research, agricultural industry, and policy sectors. Initial interviewees were identified based on AFT's existing relationships; additional producer interviewees were identified based on their survey responses. Interview participants were incentivized with a $100 gift-card.

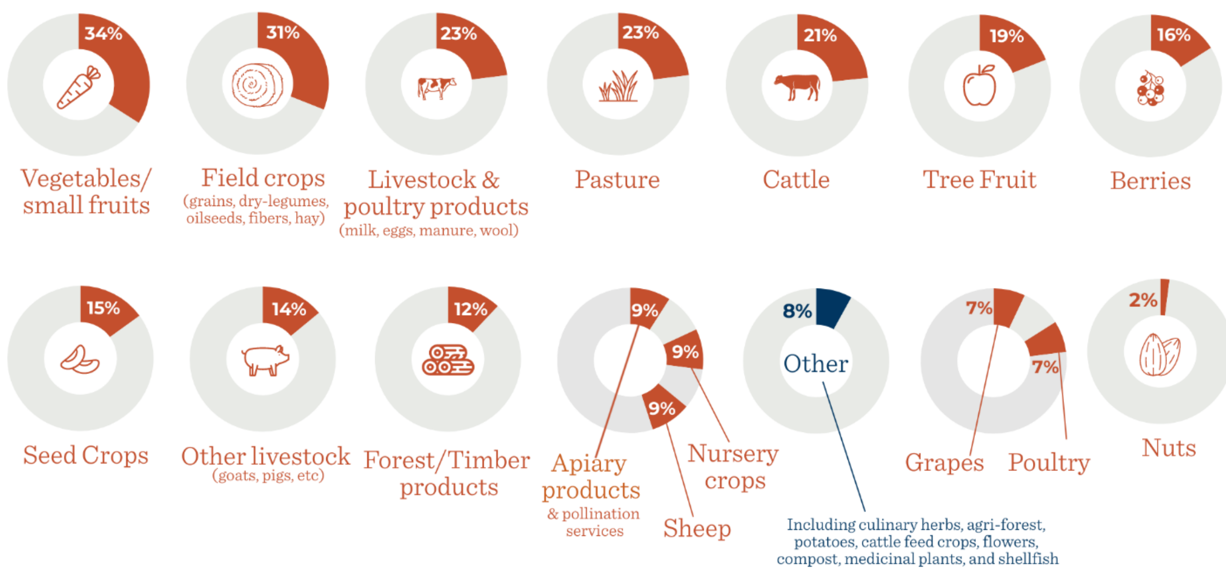


Figure 42. High-quality survey responses by production type (respondents could choose multiple types).

Notably, although tree fruit in eastern Washington is the most likely system for agrivoltaics in Washington, this demographic represented a relatively small proportion of respondents (Figure 42 and Figure 43). In contrast, field crop producers were a dominant respondent type. This is an important finding because field crops (e.g., grains) are not typically amenable for agrivoltaics and yet represent a dominant crop type near energy infrastructure and therefore are in higher conflict with solar energy development. Additionally, western Washington respondents include an abundance of vegetable producers in addition to a diversity of other crop types, underscoring the need for additional work to support solar energy considerations in smaller, diversified farming systems in this part of the state.

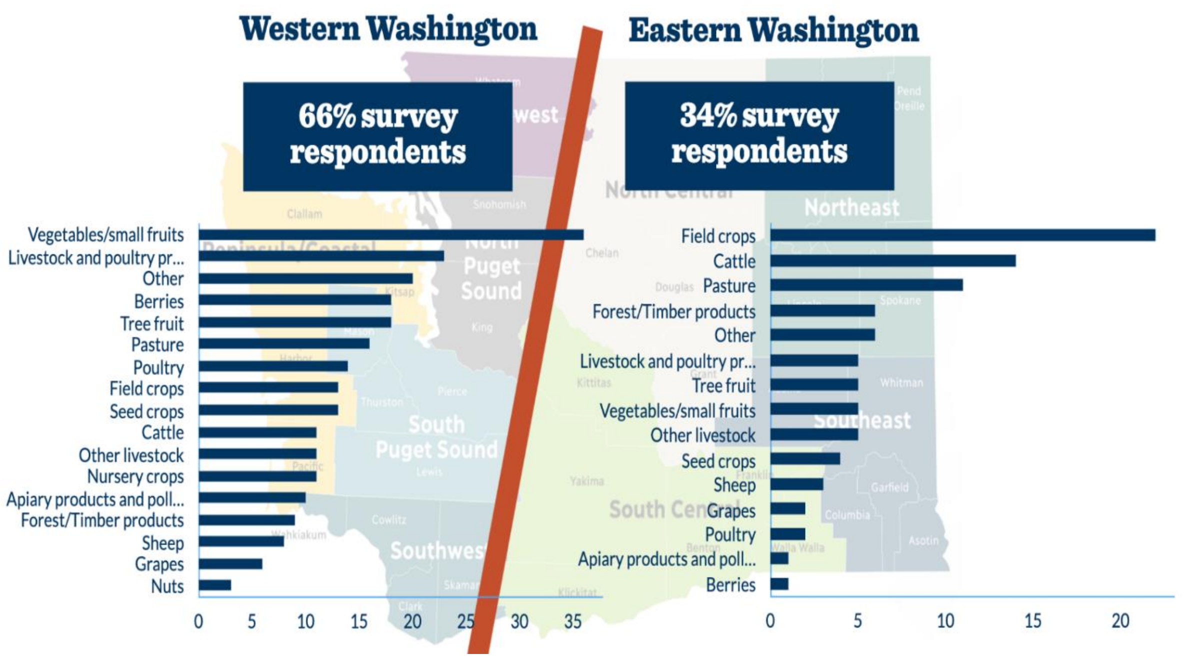


Figure 43. Survey respondents by geography and cropping system

Producer Sentiments Toward Solar Energy

Results from the survey indicate moderate interest in agrivoltaics among Washington farmers and ranchers, support which varies by geography and production system, and a host of unanswered questions about agrivoltaics deployment. Additionally, the findings highlight potential opportunities for agrivoltaics deployment for Washington's apple industry, and challenges for agrivoltaics deployment centered around community concerns.

Among respondents, support for general solar projects on agricultural land is evenly split, with 38% of respondents supporting solar projects sited on farmland, and 38% of respondents in opposition (Figure 44). The remainder answered, "it depends," with a general preference for solar siting which does not displace agriculture. Producers in western Washington tended to be more supportive of solar energy on agricultural land (41% support / 32% opposed / 27% it depends) compared to producers in Eastern Washington (34% support / 49% opposed / 17% it depends). Despite these differences, a majority (56%) of respondents indicated that solar developers should *never* be allowed to build on the most productive agricultural land (e.g., USDA prime soils and soils of statewide importance). Similarly, 67% indicated that developers should *sometimes* or *always* be allowed to build on marginal or least-productive land, and 78% agreed that developers should *sometimes* or *always* be allowed to build on land that is not suitable for agriculture.

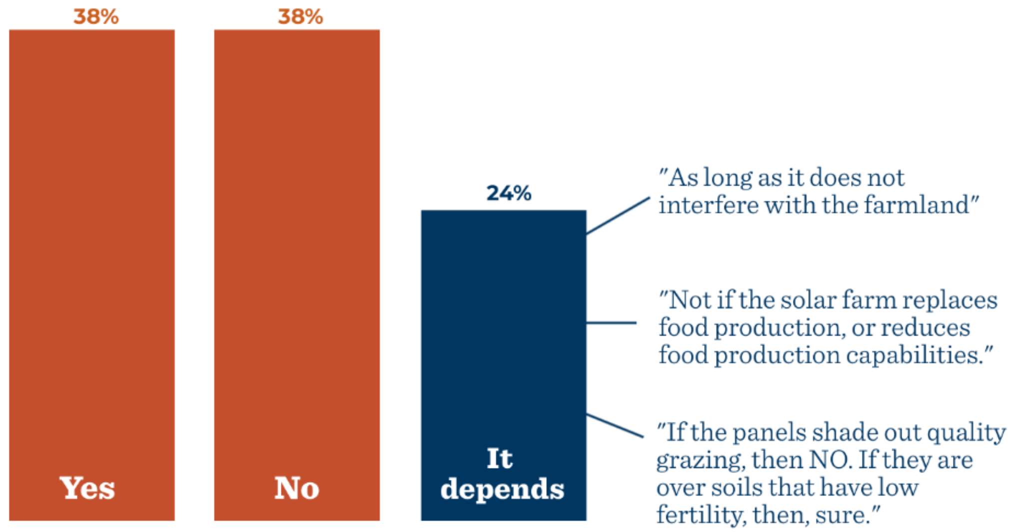


Figure 44. Support for siting solar on agricultural land by over 100 farmers surveyed across Washington.

Perceptions of the impacts of solar siting on agricultural land varied somewhat by geography, with westside producers more inclined to anticipate positive impacts from solar development (Figure 45). Even so, 50% of eastside farmers thought solar would be positive or neutral for local communities. However, a majority of producers on both sides of the Cascades project that solar siting on agricultural land will bring negative impacts to tenant farmers, farm productivity, land prices and land access, and farmland preservation.

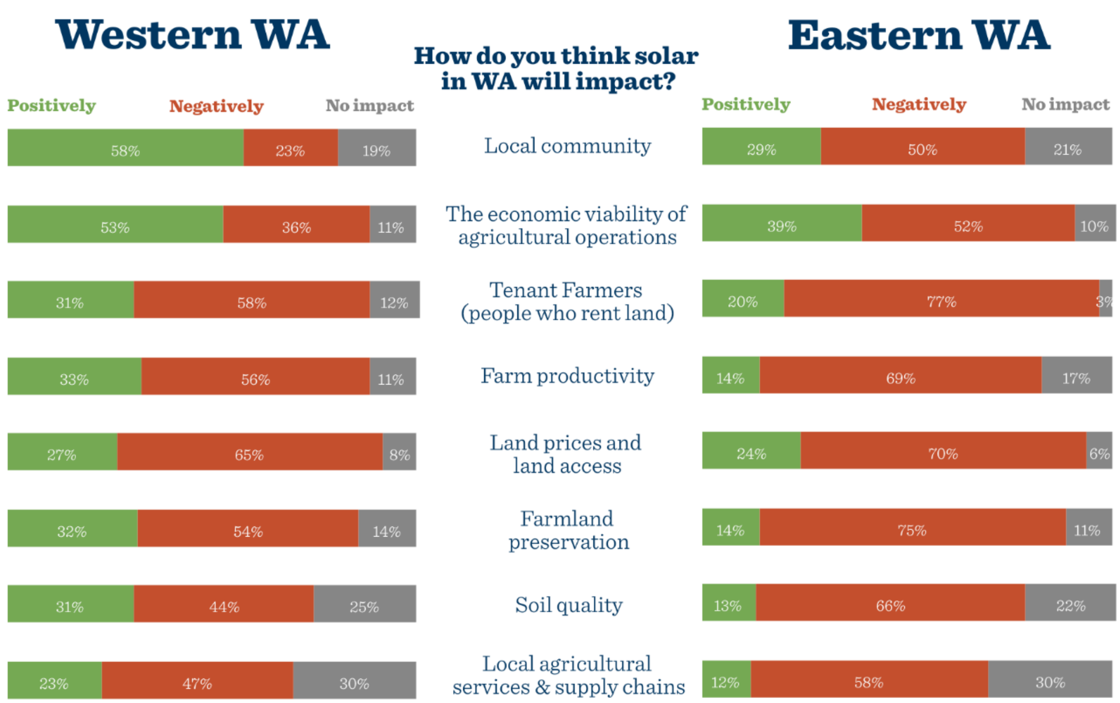


Figure 45. Anticipated impacts of solar development on agricultural land by over 100 Washington farmers surveyed

Likely contributing to these perceptions, producers across the state are already being courted by solar developers, with Eastside producers reporting more intense pressure (Figure 46). While 28% of respondents from western Washington reported being contacted by a solar developer, 38% had been contacted by 1 developer, 57% had been contacted by 2 to 5 developers, and only 5% had been contacted by more than 6. In contrast, 24% of respondents in Eastern Washington reported being contacted by a solar developer, with 80% reporting contact from 2 to 5 developers, and 20% reporting contact from 6 or more, indicating that individual eastern Washington producers are being repeatedly targeted for solar energy development requests.

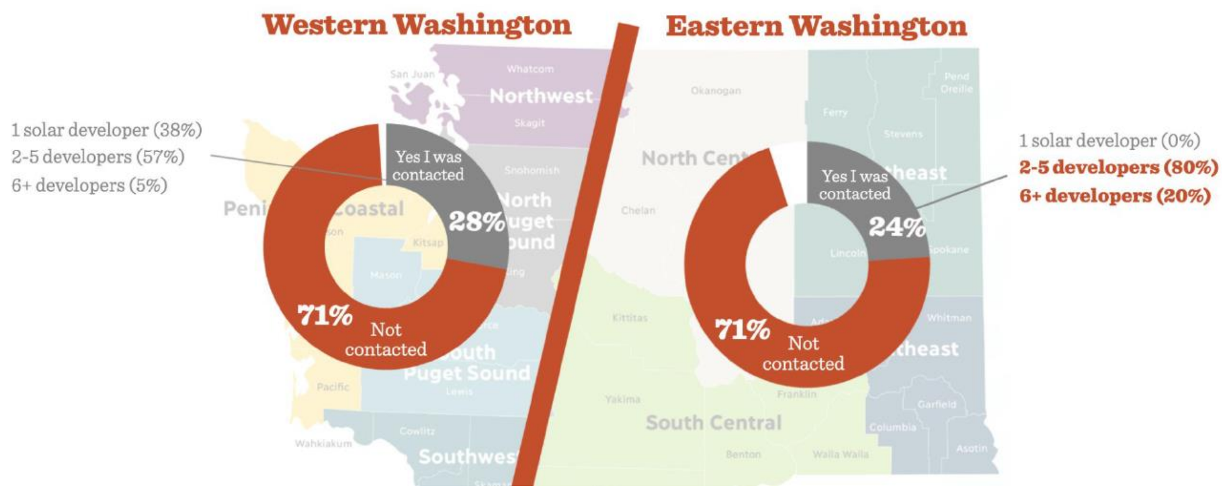


Figure 46. Reported contacts from solar developers.

Interestingly, producers of tree fruits and vegetable/small fruits tend to be more favorable to solar energy development on agricultural land than animal producers (Figure 47).

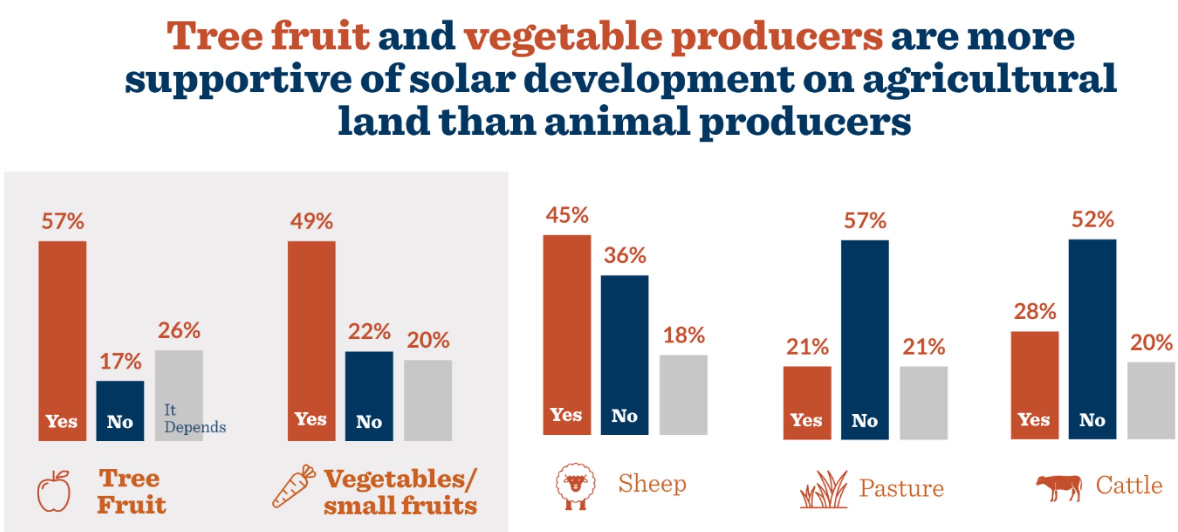


Figure 47. Support for solar development on agricultural land varies by grower type.

Producer Sentiments Toward Agrivoltaics

Approximately 60% of respondents indicated at least a basic understanding of the term "agrivoltaics", while about 40% had either never heard of it (30%) or had heard the term but didn't understand what it meant (11%). Importantly, 55% of respondents agreed that they were more likely to support solar projects on farmland after being presented with the definition of agrivoltaics and example photos of agrivoltaics projects, and 59% said they would be willing to host solar panels on their land if they could continue farming under and around the panels. This points to general receptivity to agrivoltaics among producers, at least in concept. 57% of respondents indicated that they are moderately interested or very interested in establishing an agrivoltaic system on their farm or ranch (Figure 48). However, only 24% were confident that agrivoltaics would be possible in their current production system, with 30% responding "not possible," and 41% "not sure". A key finding is that a significant majority of respondents (80%) would not consider switching production systems (i.e., crop types) in order to accommodate agrivoltaics.

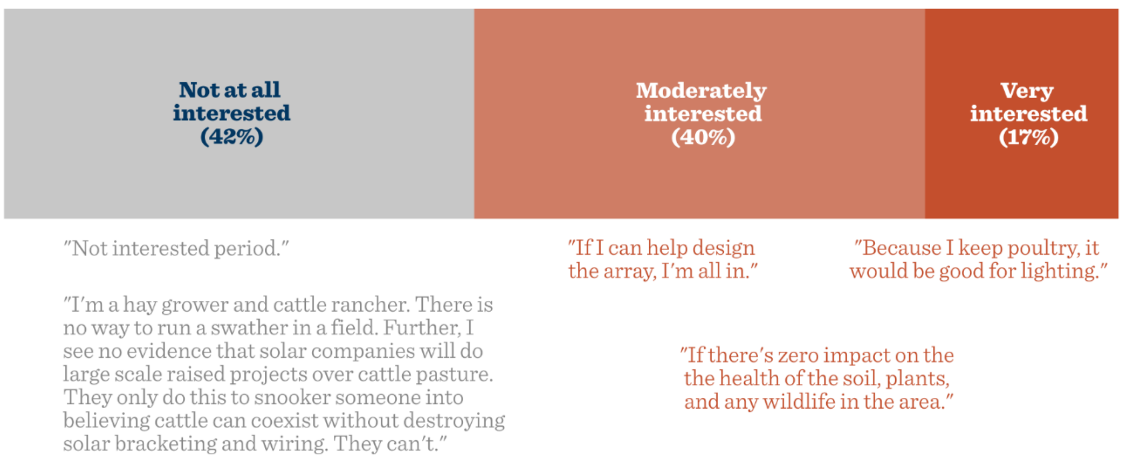


Figure 48. Producer interest in establishing agrivoltaics on their operations.

Farmers and ranchers interested in adopting agrivoltaics cited interest in stable income from the solar, expanding rural power infrastructure to support agricultural operations, and providing shade for crops and animals which can benefit from reduced direct sunlight exposure. Among survey respondents who are *not* interested in hosting agrivoltaics, there remains intense skepticism about the compatibility of agriculture and solar. Producer hesitancy around agrivoltaics included concerns over aesthetic impacts and uncertainties around solar panel decommissioning as well as impacts to agricultural yield, navigating equipment around panels, impacts to soil, and more (Figure 49).

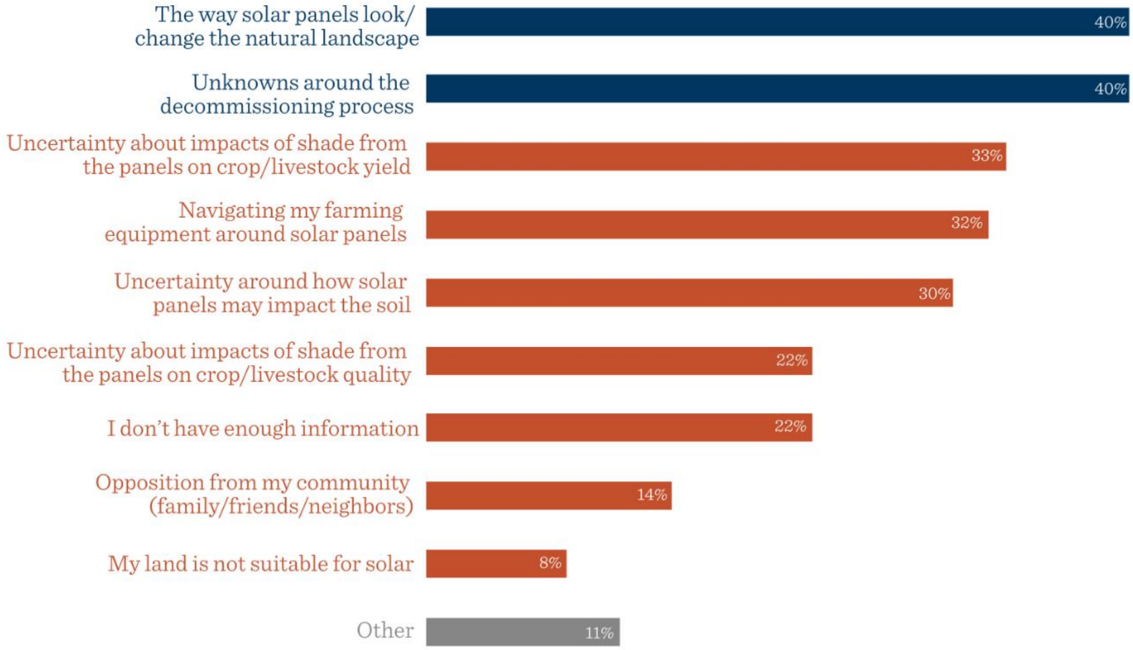


Figure 49. Producer concerns about agrivoltaics.

.

Finally, the survey results and stakeholder interviews clearly point to integration of livestock as the easiest production system to combine with solar. 86% of interviewees agreed that sheep or other livestock grazing are the best fit for agrivoltaics. Meanwhile, when survey respondents were asked about what types of activities would be possible on their land under and around solar panels, 44% indicated that grazing sheep would be possible and 42% suggested that other livestock (e.g. cattle, poultry) would be possible. This stands in contrast to responses about annual food crops (34% responded yes), perennial food crops (34%), and navigating tractors and other farming equipment (28%).

Conclusions

Given the relative nascency of agrivoltaics, many unanswered questions about this topic remain for Washington's agricultural stakeholders. Key unanswered questions about agrivoltaics include:

- **How much will it cost?**
  Can a farmer afford to do this? How will costs and benefits be shared between solar developers, utilities, and farmers? What funding is available for farmers to adopt agrivoltaics?

- **What is the business arrangement with the solar company?**
  What contracts need to be executed between the solar company and the landowner? How do these contracts and lease agreements change with a tenant farmer? What protections exist for the farmer and landowner? What resources are available to help farmers and landowners navigate this new set of

complex business relationships?

- **What is proven to work?**
  Which crops and livestock are proven to work in my region? Which crop varieties work best? How will agrivoltaics impact crop yield and quality? What types of solar designs are feasible for agrivoltaics? How will agrivoltaics affect planting and harvesting schedules?

- **How much flexibility will this afford producers?**
  Will agrivoltaics be compatible with automated farm machinery? Will agrivoltaics allow producers flexibility to change crops, machinery, or practices in the future?

In addition to the survey and stakeholder interviews, AFT also conducted two case studies on agrivoltaics development in Washington, one focusing on orchard agrivoltaics for apples, and another on an unsuccessful solar grazing project in San Juan County.

Washington's Apple Industry could be well-suited for agrivoltaics given its high capital intensity to establish orchards, potential agricultural benefits from shade, and large-scale vertical integration of the industry which could provide straightforward offtake agreements for power production. Physiological rot of apples from excess fruit surface temperatures is a major problem for the apple industry and alternative solutions (e.g., shade cloth, evaporative cooling, spraying) all have unique problems and ongoing costs. Agrivoltaics represents a potential win-win solution which turns a maintenance cost into a revenue stream for producers, though it may be challenged by the need for producer flexibility to replant orchards during the solar project lifespan. Key opportunities for agrivoltaics in apple orchards are deployments on high-value apple varieties (e.g., Honeycrisps) and solar designs which are compatible with future automation technologies without imposing excessive structural costs for the array. Future agrivoltaic technologies which utilize adaptive solar tracking to manage fruit surface temperatures and integrate alternative evaporative cooling may be uniquely suited to help Washington's apple industry adapt to increasing summer temperatures.

Agrivoltaics in San Juan County is a unique case study of agrivoltaics being rejected by a community in Washington. In theory, the San Juan Islands should be ideal for agrivoltaics given significant farmland constraints, high energy costs, and energy resilience challenges. Orcas Power & Light Cooperative (OPALCO) is a member-owned electric cooperative serving San Juan County. In 2019, OPALCO purchased "derelict farmland" at Bailer Hill on San Juan Island and fast-tracked the site for solar development to begin in 2020. After meeting with farmers, OPALCO sought to address concerns about farmland loss in the county by converting the site to a sheep grazing agrivoltaics site. Ultimately, concerns about costs, viewshed impacts, county land use permitting delays, and community opposition led to the project being indefinitely paused in January 2025. This stalled solar development highlights the urgent need for early community engagement on solar projects and greater cross-sector collaboration to ensure that farmers' voices are heard early in the solar development process.

Together, the farmer survey, stakeholder interviews, and case studies point to the need for novel cross-sector collaboration, the upfront costs of agrivoltaics, and the existing challenges of solar development as key barriers to agrivoltaics deployment in Washington State.

Cross-sector collaboration is a key aspect of agrivoltaics development to ensure projects are both suitable for agricultural production and economically viable for solar companies. From the producer perspective, agrivoltaic projects are significantly more complex than traditional shade cloth and may limit the types of production feasible on a site. Additionally, producers have concerns about solar development, construction, and operations, including potential soil impacts, livestock escaping from gates left open, and relationships with neighbors. This highlights the need for increased coordination and communication between farmers and developers throughout the project lifecycle. Significantly more work needs to be done to build trust between farmers and solar developers to support these collaborations.

Upfront costs are another challenge for agrivoltaics, particularly for developers who are trying to sell wholesale power at a competitive price. While certain applications (e.g., orchards) may have an agricultural benefit from the shade, this benefit is not reflected in the price of power generated from the system unless there is a purchaser willing to pay a premium for the power, or policy mechanisms which mitigate the upfront costs or increase revenue for agrivoltaics projects.

Finally, solar development in Washington already faces significant hurdles, which makes developers less willing to modify their process or designs in a way that may increase costs or delay project timelines. Historically, Washington has benefitted from low-cost hydropower, but these low energy costs make it more difficult for small- to medium-scale (i.e., less than 5 MW) solar to be cost-competitive, especially without a viable community solar market in the state. For utility-scale solar, the interconnection process represents a major barrier which has limited solar deployment in Washington.

Potential opportunities to address these barriers include:

- **Funding for Pilots and Demonstrations:** Farmers and developers alike remain skeptical of the scalability of agrivoltaics. State funding for pilot and demonstration projects can mitigate risk for early adopters of agrivoltaics and enable these sites to serve as valuable public engagement tools with producers, demonstrate possible agrivoltaic crops and configurations, and spur cross-sector collaboration.

- **Case Studies:** The top five most trusted sources of information on agrivoltaics for farmers and ranchers in Washington are, in order: conservation districts (52% of respondents), extension services (48%), farm associations (40%), neighbors/fellow farmers (31%), and state agencies (29%). Case studies of agrivoltaics projects from these groups would be a valuable tool to help producers evaluate the potential economic and agronomic tradeoffs of agrivoltaics for their operation.

- **Adoption of Smart Solar Siting Practices:** Agrivoltaics is a promising solution to improve land use efficiency and increase acceptance of solar sited on farmland, but it should not be viewed as a panacea to solar siting challenges. Many agricultural stakeholders remain skeptical of agrivoltaics and hold serious concerns about solar development impacting tenant farmers, land prices, farmland preservation, farm productivity, soil quality, and local farm economies. Smart Solar siting practices which support development on land not well-suited for farming and safeguard soils throughout the lifetime of solar projects should remain as a key pillar of solar siting strategy in Washington to assuage community concerns regarding solar development.

Case Studies

To inform our reporting and particularly our agrivoltaic modeling modeling analysis, we met with the following 11 farmers and toured their farms in eastern and western Washington: Austin Allred (Royal Dairy), Shane Stonemetz (Stonemetz Orchards), Jamie Baird (Baird Orchard), Chad Kruger (WSU TFREC), Freddy Arredondo (CaveB Vineyards), Shanna and Jeremy Visser and Kirk Shroyer (Natural Milk Dairy), Mia Devine and Chris Henderson (Small Acres), Andrew Byers (Finn River), Ray Williams (YES Farm), Jamese Kwele and Cathy Satava (Centralia 43), and Danielle Mills and Joe Zamboldi (Amadeus Farm). In addition, we met with Dr. Markus Keller and Lav Khot at WSU Prosser to understand viticulture and agrivoltaic compatibility. The goal of these conversations was to understand the types of farm infrastructure, management, and regulatory conditions that would be conducive towards or present challenges to agrivoltaics in their cropping or livestock systems. Below we summarize insights about agrivoltaics and general solar energy feasibility based on these visits and interviews.

Across many farmers:

- **Economic opportunities**: All farmers mentioned the need for a predictable income stream. Many responded favorably to an additional income from $2000-$3000/acre lease for solar development if given the ability to continue growing food underneath.
- **Technical concerns**:
    - For any systems that require overhead racking of panels at above standard heights (e.g., greater than 4-6 feet), there were concerns raised about whether the elevated solar arrays would be wind resistant since most farms are situated in windy locations.
    - Pilots across multiple cropping systems are needed to understand growth and management before scaling up.
- **Regulatory concerns**: All farmland are subject to impervious surface cover regulations (e.g., impervious cover cannot exceed 5% in Whatcom County). It is unclear whether solar and specifically agrivoltaics should be exempt from this regulation if not, what percentage of a solar array would count towards percent impervious cover.
- **Regulatory concerns**: There are limitations to behind-the-meter installations due to unfavorable net metering policies (e.g., Whatcom county does now allow compensation for net generation with maximum power caped at 100 kW) and/or very low electricity rates (e.g., $0.04/kWh in Grant County and $0.045 in Adams County) which makes it less economic to self-generate electricity onsite.

Table/Dessert Fruit Orchards:

- **Technical and management concerns:**
    - Racked panels must be over rows and not between rows because of mowing and tractors for spraying. This precludes vertical bifacial panels.
    - Most orchards rows are oriented north-south, which means single axis tracking and not fixed tilt panel are likely to be most appropriate, unless fixed tilt panels are racked in a perpendicular configuration.
    - The degree and frequency of spraying (e.g., including clay; typically 3-4 times per year) may require orchard specific customization of cleaning or protection of panels. Spraying occurs as a midst and is meant to cover the entire tree, including up to the canopy, which may also coat the panels and panel structures.
- **Economic opportunities due to climate related risks:**
    - Certain high value apple varieties (Honeycrisp and Cosmic Crisp) and cherries are highly susceptible to sunburn due to high fruit surface temperature and UV-B radiation.
    - Capital costs for trellising and shade cloths have the potential for offsetting the additional costs associated with racked panels (at 13 ft above ground). For example, trellising systems cost $4000/acre for poles and $2000-$13,000/acre for shade cloth installation.

- Tree fruits are susceptible to damage due to late frost. Overhead solar panels can provide insulation (up to 4 degrees F based on published studies) and complement existing mitigation methods (wind machines and irrigation).

Cider Apple Orchards

- **Technical and management concerns:**
  - Cider orchardists are not motivated by the shading benefits of agrivolatics for cider apples, and they are concerned that shade would lead to reductions in yield. Fruit quantity is more important than fruit quality because fruit quantity will directly impact cider volume. As a result, cider orchardists are less concerned about heat stress. However, excessive heat stress can cause fruit to rot.
  - Retrofit is compatible with cider orchards but, like with dessert apples, compatibility with spraying will need to be addressed.
- **Economic opportunities:**
  - Cideries have high energy demand (for apple press, heating of cold stored fruit, pasteurization) that can be met through onsite solar generation.
  - Other dual-use opportunities for solar energy on cideries that could provide economic value without negatively impacting fruit yield include use as hedgerows and wind breaks.
  - Environmentally-friendly marketing can be a component of the cider business which might align with agrivoltaics

Vineyards

- **Technical and management concerns:**
  - Shading existing grapevines with panels will likely change growth patterns which will require cascading changes to management regimes. This is because vines adapt to growing conditions within 4-5 years of planting. Introducing shaded conditions from solar panels through new plantings would avoid suddenly negatively impact optimized growth in retrofit systems.
  - Additionally, retrofit over existing vineyards will likely not work due to row-straddling mechanization and the fact that existing spacing between rows is optimized for current machinery.
  - Some solar system mounting designs may be compatible with new plantings that are designed to have variable or larger row spacing.
- **Economic opportunities due to climate related risks:**
  - There is growing concern about sunburn in grapes, which is currently being mitigated using evaporative cooling (largely in Washington) or shade cloths. However, this is regionally dependent, as some vineyards located in central Washington are in a cooler climate compared to other wine growing regions in eastern Washington like Walla Walla and Prosser.
  - For wine grapes, quality of fruit is more critical than quantity. The industry norm is that high quality is obtained through lower yields, but 5-10% *increases* in yield should be acceptable (relationship between quality and yields is constant at this range of yields).

Small vegetable farmers

- **Opportunities**:
  - Small farmers are likely going to be 'behind the meter' due to the farm size and proximity to an existing substation. In some counties where net energy metering does not compensate for net positive generation), farmers will not have an incentive to build larger systems and supply the grid despite having the land area to do so. Assuming small farmers are primarily interested in offsetting their own electricity consumption, growing some crops underneath a small, slightly elevated (6-8 ft) array would be relatively low risk.
  - Certain crops that are more vulnerable to heat stress, such as lettuce and brassicas, are of higher value in direct sell markets (CSA, farmers markets). Farmers expressed a desire to be

able to plant more of these crops if conditions were more favorable. These crops are known to perform well under shaded conditions.

Dairies

- **Technical and management concerns:**
  - Solar arrays over cattle living areas like corrals would be exposed to urea and ammonia vapors that could corrode metal infrastructure and are known to reduce the lifetime of roof materials. If lifetimes are less than that of the solar panels (typically 25-30 years), then rooftop solar directly above high concentrations of cattle may not be appropriate.
- **Opportunities:**
  - Because dairies are already trying to reduce emissions through manure management and enteric fermentation reduction, they may be promising candidates for green energy incentives.
  - Pastureland on which organic cattle are grazed, solar may be racked at heights to allow grazing underneath and provide shade.
  - Dairies offer opportunities for colocation, as opposed to agrivoltaics through retrofitting existing infrastructure such as barns and shade structures. In hot climates (eastern Washington) where additional shade structures are needed, canopy solar arrays are being considered.
  - Dairies have high energy requirements that do not vary seasonally. Critical loads include milking and cleaning machinery that need to be operated daily. For a dairy operation with about 4000 heads, electricity costs can exceed $10,000/month. In western Washington, storm induced power outages have become more frequent and prolonged (several hours to multiple days). Farmers have currently responded by running diesel generators, presenting an opportunity for onsite solar energy generation and storage to provide climate resiliency, especially if net energy metering rates are favorable.

Opportunities to Advance Agrivoltaics in Washington

Apart from sheep grazing under standard utility-scale ground-mounted solar, intervention is necessary to significantly accelerate the development of agrivoltaic projects in Washington. Although agrivoltaics is not a panacea for solving Washington's renewable energy siting challenges, it can be a substantial component in helping Washington meet its renewable energy goals while navigating tension surrounding solar energy siting on ecologically-, culturally-, and agriculturally-important lands. Our analysis suggests agrivoltaics could make a significant contribution to Washington's energy and farming future. Below we outline eight opportunity areas for Washington to consider for increasing deployment of agrivoltaics.

1. **Invest in place-based research and demonstration projects**. Washington State University (WSU) has a world class agricultural research and outreach program in addition to the Institute for Northwest Energy Futures. Targeted investment by the state into crop-specific and region-specific agrivoltaic viability research would accelerate our understanding of which crop types, varieties, solar panel infrastructure and designs, and geographies are most suitable for agrivoltaics in Washington. Further, with WSU leading this research, promising results are more likely to be taken up by producers. Indeed, our survey results show that farmers strongly trust WSU's agricultural extension offices. Additionally, engaging industry partners (e.g., the various fruit commissions) in this research would help Washington approach agrivoltaics through the lens of the agricultural industry in addition to the energy industry. Ultimately, energy developers are likely to avoid projects that are not scalable, and which require substantial bespoke deviations from normal project considerations. Research that can identify scalable agrivoltaic solutions that avoid intensive customization to each property could aid in deployment. Although scalability is likely key in many instances, understanding if and how small, diversified producers could participate in agrivoltaics will also be useful to research.

2. **Provide farmers with accessible information**. Besides WSU, producers we surveyed expressed strong trust in conservation districts as honest sources of reliable information. Engaging the Washington State Conservation Commission and districts and providing them with accessible information on the state of science on agrivoltaics, other forms of colocating solar on farmland (e.g., pivot corners, dairy infrastructure), regulatory opportunities and constraints, and funding models, could help socialize the idea of agrivoltaics. Farmers are unlikely to have the capacity to sift through reports and myriad studies and so providing technical assistance to farmers on how to implement agrivoltaics will be key.

3. **Develop forums for agricultural producers, energy developers, and county and state regulators to work together.** Social science research as well as Washington farmers surveyed in our own study here are clear that agrivoltaics will be most successful if farmers are part of the process from the beginning. Similarly, survey data generally suggests that energy developers are skeptical of the regulatory landscape and financial viability of agrivoltaics projects. Creating spaces for the agricultural community and energy developers to discuss where and how agrivoltaics could function and what regulatory clarity or changes would be needed could improve community and government acceptance for agrivoltaics. The Washington State Department of Commerce may be an ideal organizing entity for this work, especially because it houses both an Energy Division and Growth Management Services. Alternatively, there may be value in considering a new agency office to coordinate the knowledge, financing, regulations, guidance, and incentives related to agrivoltaics and other energy deployment on agricultural land. Coordination among agencies (e.g., Commerce, Utilities and Transportation Commission, DNR, WSDA) will be essential.

4. **Explore policy pathways for agrivoltaics in Washington.** Existing research presents legal and policy opportunities for agrivoltaics and also compares, contrasts, and critiques existing policies and incentive structures elsewhere (Guarino and Swanson 2022, Marzillier 2023, Wiseman 2023, Dupraz 2024, Ferreiro et al. 2024, Smith 2025). This literature explores net-metering and feed-in tariff structures, tax and zoning adjustments, as well as policy ideas for allowing exhausted agricultural land to rest under solar panels while recovering groundwater and soil health. There is also a recent thesis exploring agrivoltaics in the context of Washington's Growth Management Act (Smith 2025). Agency and legislative staff – along with Tribes and stakeholders – could study this literature to determine which policies might be most effective in the Washington context. Such an analysis would necessarily include an understanding of how Washington works in the federal system (e.g., with the Rural Energy for American Program – REAP, Conservation Reserve Program – CRP, etc.) and what the role of county regulations versus Washington's Energy Facility Siting and Evaluation Council (EFSEC) is. One dimension this work might consider is whether county-level moratoria on solar energy drive developers to EFSEC, bypassing county review and displacing farmland. If so, agrivoltaics might ease that tension. Ultimately, Washington could create guidelines for viable agrivoltaic projects, as has been done in Italy.

5. **Implement financial incentives.** Research shows that agrivoltaics will be challenging to make feasible in many cases without government financial support. If Washington wants to promote agrivoltaics, understanding what financial incentives (e.g., taxes, loans, rate adjustments) are possible will be helpful. Such an analysis would include an understanding of what financial structures are most appropriate, whether a farmer-owned versus leased project is more effective, what scale or project is most viable, which counties might be most effective, etc. Further, developing sample contracts to inform agrivoltaics deployment would add clarity for farmers as to how agrivoltaics might be operationalized. These contracts would also necessarily require consideration of other costs and subcontracts (e.g., for vegetation maintenance, insurance for electrocution or crop damage). Understanding if, and to what extent, public-private partnerships are important to secure the land base as well as developer and agricultural producer interest may also be important.

6. **Build new energy infrastructure.** Our mapping shows that there is already great potential for agrivoltaics on land that is in close proximity to substations. However, the vast majority of agricultural land – including amenable crop types – is further from substations. Solar energy projects can connect directly to transmission or distribution lines, but only a limited number of projects can do so. Increasing the number of substations and appropriate transmission capacity – as well as targeted substation siting near crop types that are amenable for agrivoltaics – could expedite the implementation of agrivoltaics. Pairing this work by engaging agricultural communities early in the process could facilitate not only substation development but also agrivoltaic (and other "Smart Solar (SM)") energy deployment.

7. **Elevate opportunities for non-agrivoltaics "Smart solar (SM)" that integrate solar and crop production.** We have already identified tens of thousands of acres of pivot corner lands – including near substations – that could provide multiple gigawatts of solar energy. Other opportunities include placing solar on top of shade structures for livestock, feed lots, etc. Conservation Reserve Program (CRP) lands may also opportunities to explore for solar deployment. These former agricultural lands could benefit from solar energy if ground disturbance is minimized and if paired with solar grazing. The Goose Prairie solar farm in Washington that is now testing sheep grazing was former CRP land and so there is precedent for this approach in Washington.

8. **Consider public land as an opportunity for agrivoltaics.** We identified several thousand acres of potential agrivoltaic land that is owned by the Washington State Department of Natural Resources (DNR), most of which does not currently appear on the DNR 'Clean Energy Parcel Screening' tool. DNR is required to generate revenue from its lands and agrivoltaics might be an opportunity generate additional revenue while potentially providing financial benefits to farmers who currently lease that land. Those benefits could include reduction in lease rates, savings on irrigation, or increased crop production or quality.

Literature Cited

Adeh, E. H., Good, S. P., Calaf, M., and C. W. Higgins. 2019. Solar PV power potential is greatest over croplands. Scientific Reports 9: 11442.

Ahn, S. Y., Lee, D. B., Lee, H. I., Myint, Z. L., Min, S. Y., Kim, B. M., Oh, W., Jung, J. H., and H. K. Yun. 2022. Grapevine growth and berry development under the agrivoltaic solar panels in the vineyards. Journal of Bio-Environmental Control 31: 356-365.

Al-agele, H. A. 2020. Measuring tomato production and water productivity in agrivoltaic systems. Thesis. Oregon State University.

AL-agele, H. A., Proctor, K., Murthy, G., and C. Higigins. 2021. A case study of tomato (*Solanum Lycopersicon* var. *Legend*) production and water productivity in agrivoltaic systems. Sustainability 13: 2850.

American Farmland Trust. 2022. Farms Under Threat 2040. Choosing an abundant future. https://farmlandinfo.org/wp-content/uploads/sites/2/2022/08/AFT_FUT_Abundant-Future-7_29_22-WEB.pdf

Andrew, A. 2020. Lamb growth and pasture production in agrivoltaic production system. Thesis. Oregon State University.

Andrew, A. C., Higgins, C. W., Bionaz, M., Smallman, M. A., and S. Ates. 2021a. Pasture production and lamb growth in agrivoltaic system. AgriVoltaics 2020 Conference. AIP Conference Proceedings 2361: 060001. DOI:10.1063/5.0055889

Andrew, A. C., Higgins, C. W., Smallman, M. A., Graham, M., and S. Ates. 2021b. Herbage yield, lamb growth and foraging behavior in agrivoltaic production system. Frontiers in Sustainable Food Systems. DOI:10.3389/fsufs.2021.659175

Andrew, A. C., Higgins, C. W., Smallman, M. A., Prado-Tarango, D. E., Rosati, A., Ghajar, S., Graham, M., and S. Ates. 2024. Herbage and sheep production from simple, diverse, and legume pastures established in an agrivoltaic production system. Grass and Forage Science 79: 294-307.

Arias-Navarro, I., Del Campo-Gomis, F. J., Agullo-Torres, A. M., and A.Martinez-Poveda. 2023. Environmental sustainability in vineyards under a protected designation of origin in view of the implementation of photovoltaic solar energy plants. Land 12: 1871.

Asa'a, S., Reher, T., Ronge, J., Diels, J., Poortmans, J., Radhakrishnan, H.S., van der Heide, A., Van de Poel, B., and M. Daenen. 2024. A multidisciplinary view on agrivoltaics: future of energy and agriculture. Renewable and Sustainable Energy Reviews 200: 114515.

Basore, P., Dummit, K., Ellis, C., Peng, P., Benoliel, P., Hendrickson, T., Feldman, D., Ramasamy, V., Woodhouse, M.,m Zuboy, J., Desai, J., Walker, A., Braid, J., Jost, N., and E. Cooper. 2024. Solar Photovoltaic System Cost Benchmarks. Solar Energy Technologies Office. https://www.energy.gov/eere/solar/solar-photovoltaic-system-cost-benchmarks.

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vegopolan, N., Berg, A., and E. F. Wood. 2018. Present and future Koppen-Geiger climate classification maps at 1-km resolution. Scientific Data 5: 180214.

Bellone, Y., Croci, M., Impollonia, G., Zad, A. N., Colauzzi, M., CAmpana, P. E., and S. Amaducci. 2024. Simulation-Based Decision Support for Agrivoltaic Systems. *Applied Energy* 369: 123490. https://doi.org/10.1016/j.apenergy.2024.123490.

Bernton, H. 2018. Solar panels on farmland? I Central Washington, that stirs a fight. Seattle Times, 27 April 2018. https://www.seattletimes.com/seattle-news/environment/solar-panels-on-farmland-in-central-washington-that-stirs-a-fight/

Birchall, M., Hussain, S. N., and A. Ghosh. 2025. Review of agrivoltaic demonstration site studies with comparable configurations for a UK-based application. Solar Compass: 100135.

Block, B. 2025. The obscure state agency that referees WA's green energy battles. The Energy Facility Site Evaluation Council has power to overrule local zoning laws – putting it at the center of a backlash to renewable energy. Cascade PBS, 04 March 2025. https://www.cascadepbs.org/investigations/2025/03/obscure-state-agency-referees-was-green-energy-battles

Boini, A., Manafrini, L., Morandi, B., Grappadelli, L. C., PRedieri, S., Daniele, G. M., and G. López. 2021. High Levels of Shading as A Sustainable Application for Mitigating Drought, in Modern Apple Production. *Agronomy* 11 (3): 422. https://doi.org/10.3390/agronomy11030422.

Bolinger, M. and G. Bolinger. 2022. Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density. *IEEE Journal of Photovoltaics* 12 (2): 589–94. https://doi.org/10.1109/JPHOTOV.2021.3136805.

Bowen, M. and F. Chudleigh. 2024. Agrivoltaic grazing systems in Queensland. The potential, challenges, and opportunities for the co-existence of grazing and solar power plants in Queensland. State of Queensland.

Brent, A. 2024. PREPRINT. Systems for dairy farming in Aotearoa New Zealand: a cost-benefit analysis. Available at SSRN: DOI:10.2139/ssrn.5023366.

Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M. H., Ruget, F., Nicoullaud, B., Gate, P., Devienne-Barret, F., Antonioletti, R., Durr, C., Richard, G., Beaudoin, N., Recous, S., Tayot, X., Plenet, D., Cellier, P., Machet, J.-M., Meynard, J. M., and R. Delecolle. 1998. STICS: A Generic Model for the Simulation of Crops and Their Water and Nitrogen Balances. I. Theory and Parameterization Applied to Wheat and Corn. *Agronomie* 18: 311–46. https://doi.org/10.1051/agro:19980501.

Bruno, M. 2023. Tracking optimization in agrivoltaic systems. A comparative study for apple orchards. THESIS. KTH Industrial Engineering and Management.

Brunswick, S. and D. Marzillier. 2023. The New Solar Farms: Growing a Fertile Policy Environment for Agrivoltaics. Minnesota Journal of Law, Science & Technology 24: 123.

Buzzelli, M. 2024. When is agrivoltaics profitable compared to agriculture and photovoltaics? A joint-product economic feasibility analysis. Thesis. Colorado State University.

Campana, P.E., Stridh, B., Amaducci, S., and M. Colauzzi. 2021. Optimisation of Vertically Mounted Agrivoltaic Systems. *Journal of Cleaner Production* 325: 129091. https://doi.org/10.1016/j.jclepro.2021.129091.

Carreno-Ortega, A., do Paco, T. A., Diaz-Perez, M., and M. Gomez-Galan. 2021. Lettuce production under mini-PV modules arranged in patterned designs. Agronomy 11: 2554.

Carrausse, R. and X. A. de Sartre. 2023. Does agrivoltaism reconcile energy and agriculture? Lessons from a French case study. Energy, Sustainability and Society 13: 8.

Chae, S.-H., Kim, H. J., Moon, H.-W., Kim, Y. H., and K.-M. Ku. 2022. Agrivoltaic systems enhance farmers' profits through broccoli visual quality and electricity production without dramatic changes in yield, antioxidant capacity, and glucosinolates. Agronomy 12: 1415.

Chalgynbayeva, A., Balogh, P., Szollosi, L., Gabnai, Z., Apati, F., Sipos, M., and A. Bai. 2024. The economic potential of agrivoltaic systems in apple cultivation – a Hungarian case study. Sustainability 16: 2325.

Cho, J., Park, S. M., Park, A. R., Lee, O. C., Nam, G., and I.-H. Ra. 2020. Application of photovoltaic systems for agriculture: a study on the relationship between power generation and farming for the improvement of photovoltaic applications in agriculture. Energies 13: 4815.

Columbia Basin Restoration Initiative. 2023. A proposal to the Biden Administration from the "Six Sovereigns". Confederated Tribes and Bands of the Yakama Nation, Confederated Tribes of the Umatilla Indian Reservation, Confederated Tribes of the Warm Springs Reservation, Nez Perce Tribe, State of Oregon, State of Washington. 2023 Columbia Basin Restoration Initiative.

Columbia River Inter-Tribal Fish Commission. 2022. Energy Vision for the Columbia River Basin. https://critfc.org/wp-content/uploads/2024/06/EnergyVision-full-report.pdf

Cotton, M., Langford, S., Kuria, A., and K. Parkhill. 2025. A technology to solve the water-energy-food crisis? Mapping sociotechnical configurations of agrivoltaics using Q-methodology. Energy Research & Social Science 119: 103872.

Cuppari, R. I., Fernandez-Bou, A. S., Characklis, G. W., Ramirez, M., Nocco, M. A., and M. Abou-Najm. 2024. Drivers of agrivoltaic perception in California and North Carolina. Environmental Research Food Systems 1: 021003.

Di Domenico, G., Colantoni, A., Bianchini, L., Cecchini, M., Gallucci, F., and V. Di Stefano. 2025. Agrivoltaics systems potentials in Italy: state of the art and SWOT-AHP analysis. Sustainability 17: 925.

Disciglio, G., Frabboni, L., Tarantino, A., and A. Stasi. 2023. Association between dynamic agrivoltaic system and cultivation: viability, yields and qualitative assessment of medicinal plants. Sustainability 15: 16252.

Dinesh, H. and J. M. Pearce. 2016. The Potential of Agrivoltaic Systems. *Renewable and Sustainable Energy Reviews* 54: 299–308. https://doi.org/10.1016/j.rser.2015.10.024.

Dupraz, C. 2024. Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity. Agroforestry Systems 98: 2670-2696.

Economic Research Services. 2025. Farm Income and Wealth Statistics - Farm sector financial indicators, State rankings. U.S. Department of Agriculture. Updated February 06, 2025. https://data.ers.usda.gov/reports.aspx?ID=4048

Energy Program. 2023. Dual-use solar opportunities for Washington State. Washington State University. https://www.energy.wsu.edu/documents/630-Dual-Use_Solar_Opportunties-WSUEEP23-05.pdf

Elamri, Y., Cheviron, B., Lopez, J.-M., Dejean, C., and. G. Belaud. 2018. Water budget and crop modelling for agrivoltaic systems: application to irrigated lettuces. Agricultural Water Management 208: 440-453.

Fidelis, S. d. S. Moura, G. A. B., Fonseca, V. d. F. C., Nascimento, S. T., and. A. S. C. Maia. 2025. PREPRINT. Photovoltaic panels improve Comfort, performance and sustainability of sheep in tropical areas. Available at SSRN. DOI:10.2139/ssrn.5144192.

Folton, L. 2023. Agrivoltaisme: suivi et analyse agronomique et economique d'un protoype de houblonniere sous panneaux photovoltaïques en Sud-Vendee. Sciences du Vivant [q-bio]. Dumas-04342822

Fumey, D., Chopard, J., Lopez, G., PErsello, S., Juillion, P., Hitte, V., Elamri, Y., Dubosc, J., Tiffon-Terrade, B., Garcin, J., Malon, A., Valle, B., Christophe, A., Simonneau, T., Saurin, N., Champetier, A., Berud, F., Deveze, S., Thiery, J., Didier, V., Payan, J.-C., and F. Sourd. 2023. Dynamic agrivoltaics, climate protection for grapevine driven by artificial intelligence. 22nd GiESCO International Meeting, Group of international Experts of vitivinicultural systems for Co-Operation (GiESCO), July 2023. Cornell University, Ithaca, New York, United States. DOI:10.58233/mTZfKUqjhal-04868064

Gill, B., Rogers, M., Beverly, C., McCaskill, M., and D. Wallace. 2024. PREPRINT. Microclimate observations and pasture trials within commercial solar farms and their implications for sheep grazing agrivoltaic developments. SSRN. DOI:10.2139/ssrn.4807687

Gim, G. H., Park, J., Kim, T. Y., Kim, D. S., Kim, W., Nam, J., and C. Lim. 2020. Investigation of pear growth under foldable agrivoltaic structure. AgriSolar Clearing House. https://www.agrisolarclearinghouse.org/wp-content/uploads/2022/02/Investigation-of-Pear-Growth-Under-Foldable-Agrivoltaic-Structure.pdf

Golz, S. and F. Larisch. 2024. Acceptance of agrivoltaics – a multi-stakeholder survey for a German agrivoltaic system in fruit farming. Agrivoltaics World Conference 2022. DOI:10.52825/agripv.v1i.531

Gross, E., Chavez, M., and J. Bousselot. 2024. Chile pepper production in a Colorado rooftop agrivoltaic system. CitiesAlive: 20th Annual Green Roof and Wall Conference. 2024 Conferences Proceedings.

Guarino, J. and T. Swanson. 2022. Emerging agrivoltaic regulatory systems: a review of solar grazing. Chicago-Kent Journal of Environmental & Energy Law 12: 1.

Ha, J., Nguyen, J., and J. M. Pearce. 2024. Determinants of consumers' willingness to pay for agrivoltaic produce: the mediating role of trust. SSRN. DOI:10.2139/ssrn.4734821

Hauser, M. 2023. Agrivoltaic system validation: implementing into a raspberry farm. Thesis.

Heins, B. J., Sharpe, K. T., Buchanan, E. S., and M. H. Reese. 2022. Agrivoltaics to shade cows in a pasture-based dairy system. AIP Conference Proceedings 2635. AgriVoltaics 2021 Conference. DOI:10.1063/5.0103148

Helsen, H., Maestrini, B., MEijers, E., Hermelink, M., de Vries, W., Balk, P., and F. de Ruijter. 2022. Crop response to agrivoltaics in soft fruit production. Wageningen University and Research eDepot. https://edepot.wur.nl/588670

Hermelink, M. I., Maestrini, B., and F. J. de Ruijter. 2024. Berry Shade Tolerance for Agrivoltaics Systems: A Meta-Analysis. *Scientia Horticulturae* 330:113062. https://doi.org/10.1016/j.scienta.2024.113062.

Hernandez, V., Blasi, M. D., Genovese, M., Andrews, R., Cos, J., Contreras, F., Guevara, A., Hellin, P., and P. Flores. 2022. Agrivoltaic in a semi-aride climate: co-existence of agricultural activities in utility-scale plants of EGP for multiple and sustainable land use. Agrivoltaics World Conference 2022. The Management of Agriculture Production Under Photovoltaic Panels. DOI:10.52825/agripv.v1i.607

Hickey, T., Uchanski, M., and J. Bousselot. 2024. Vegetable crop growth under photovoltaic (PV) modules of varying transparencies. Heliyon e36058.

Hopf, M., Trommsdorff, M., and K. Wydra. 2021. Economic analysis of agrivoltaics in orchard farming in Germany. Agrivolatics Conference 2021.

Horowitz, K., Ramasamy, V., Macknick, J., and R. Margolis. 2020. Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops. NREL/TP—6A20-77811, 1756713, MainId:30726. https://doi.org/10.2172/1756713.

Hussain, S. N. and A. Ghosh. 2024. Evaluating Tracking Bifacial Solar PV Based Agrivoltaics System across the UK. *Solar Energy* 284: 113102. https://doi.org/10.1016/j.solener.2024.113102.

Jackson, A., Doubleday, K., Staie, B., Perna, A., Sabraw, M., Voss, L., Alvarez, A., Kominek, B., and J. Macknick. 2024. County land-use regulations for solar energy development in Colorado. Golden, CO. National Renewable Energy Laboratory. NREL/TP-6A20-88556.

Jamil, U. and J. M. Pearce. 2025. Experimental impacts of transparency on strawberry agrivoltaics using thin film photovoltaic modules under low light conditions. Solar Energy 290: 113375.

Jardon, C., Saudreau, M., Grechi, I., Boudon, F., Guerrier, P., and F. Normand. 2024. Agrivoltaic systems, an opportunity to mitigate the irsk of climatic hazards in apricot orchards while producing renewable energy. ISHS Plum Apricot 2024 – First International Symposium on Apricot and Plum. Avignon, France. https://agris.fao.org/search/en/providers/122439/records/67bd87f0e27dfa125189a789

Juillion, P., Lopez, G., Fumey, D., Lesniak, V., Genard, M., and G. Vercambre. 2022. Shading apple trees with an agrivoltaic system: impact on water relations, leaf morphophysiological characteristrics and yield determinants. Scientia Horticulturae 306: 111434.

Juillion, P., Lopez, G., Genard, M., and G. Vercambre. 2023. Analysis and modelling of tree shading impacts on apple fruit quality: case study with an agrivoltaic system. Acta Horticulturae 1366. Proceedings of the International Symposium on Innovative Perennial Crops Management 187-194.

Juillion, P., Lopez, G., Fumey, D., Lesniak, V., Genard, M., and G. Vercambre. 2024a. Combining field experiments under an agrivoltaic system and a kinetic fruit model to understand the impact of shading on apple carbohydrate metabolism and quality. Agroforestry Systems 98: 2829-2846.

Juillion, P., Lopez, G., Vercambre, G., Genard, M., Lesniak, V., and D. Fumey. 2024b. Specific leaf area and photosynthesis of apple trees under a dynamic agrivoltaic system. Agrivoltaics World Conference 2023. DOI:10.52825/agripv.v2i.999

Jung, D. and A. Salmon. 2022. Price for covering cropland with an agrivoltaic system: PV panels replacing shading nets in Chilean blueberry cultivation. AIP Conference Proceedings 2635: 030001.

Jurkenbeck, K. and M. Schulze. 2024. Consumer preferences and willingness to pay for apples from agrivoltaics. Journal of Cleaner Production 465: 142854.

Khera, K., Buchele, M., Neuwald, D. A. 2024. Unleashing the potential of agri-PV for cherry and apple production in Himachal Pradesh, India. 32nd International Conference of Agricultural Economists. 2-7 August 2024. New Delhi, India.

Kirimura, M., Takeshita, S., Matsuo, M., Zushi, K., Gejima, Y., Honsho, C., Nagaoka, A., and K. Nishioka. 2022. Effects of agrivoltaics (photovoltaic power generation facilities on farmland) on growing condition and yield of komatsuna, mizuna, kabu, and spinach. Environmental Control in Biology 60: 117-127.

Ko, D.-Y., Chae, S.-H., Moon, H.-W., Kim, H. J., Seong, J., Lee, M.-S., and K.-M. Ku. 2023. Agrivoltaic farming insights: a case study on the cultivation and quality of kimchi cabbage and garlic. Agronomy 13: 2625.

Kochendoerfer, N., Hain, L., and M. L. Thonney. 2019. The agricultural, economic and environmental potential of co-locating utility scale solar with grazing sheep. David R. Atkinson Center for a Sustainable Future.

Laub, M., Pataczek, L., Feuerbacher, A., Zikeli, S., and P. Hogy. 2022. Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis. Agronomy for Sustainable Development 42: 51.

Lazard. 2025. "Lazard LCOE +." https://www.lazard.com/media/uounhon4/lazards-lcoeplus-june-2025.pdf.

Loan, M., Picon-Cochard, C., Cyrille, B. de-L., Christophe, c., Luc, M., Marilyn, R., and C. David. 2022. One year of grassland vegetation dynamics in two sheep-grazed agrivoltaic systems. AIP Conferences Proceedings. Hal-03728200

Lopez, G., Chopard, J., Persello, S., Juillion, P., Lesniak, V., Vercambre, G., Genard, M., and D. Fumey. 2022. Agrivoltaic systems: an innovative technique to protect fruit trees from climate change. Acta Horticulturae. 1366. DOI:10.17660/ActaHortic.2023.1366.20

Lopez, G., Juillion, P., Hitte, V., Elamri, Y., Montrognon, Y., Chopard, J., Persello, S., and D. Fumey. 2023. Protecting flowers of fruit trees from frost with dynamic agrivoltaic systems. AgriVoltaics World Conference 2023. https://doi.org/10.52825/agripv.v2i.1002

Lytle, W., Meyer, T. K., Tanikella, N. G., Burnham, L., Engel, J., Schelly, C., and J. M. Pearce. 2021. Conceptual design and rationale for a new agrivoltaics concept: pasture-raised rabbits and solar farming. Journal of Cleaner Production 282: 124476.

Magarelli, A., Mazzeo, A., and G. Ferrara. 2024. Fruit crop species with agrivoltaic systems: a critical review. Agronomy 14: 722.

Magarelli, A., Mazzeo, A., and G. Ferrara. 2025. Climate modulation and vine benefits in the Puglia Region, Southeastern Italy. Horticulturae 11: 160.

Maia, A. S. C., Culhari, E. de. A., Fonseca, V. de F. C., Milan, H. F. M., and K. G. Gebremedhin. 2020. Photovoltaic panels as shading resources for livestock. Journal of Cleaner Production 258: 120551.

Malu, P. R., Sharma, U. S., and J. M. Pearce. 2017. Agrivoltaic potential on grape farms in India. Sustainable Energy Technologies and Assessments 23: 104-110.

Marrou, H., Wery, J., Dufour, L., and C. Dupraz. 2013. Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. European Journal of Agronomy 44: 54-66.

Mohammedi, S., Dragonetti, G., Adamane, N., and A. Fouial. 2023. The impact of agrivoltaic systems on tomato crop: a case study in southern Italy. Processes 11: 3370.

Moon, H.-W. and K.-M. Ku. 2023. The effect of additional shading utilizing agriphotovoltaic structures on the visual qualities and metabolites of broccoli. Frontiers in Plans Science. DOI:10.3389/fpls.2023.1111069

Moore, S., Graff, H., Ouellet, C., Leslie, S., and D. Olweean. 2022. Can we have clean energy and grow our crops too? Solar siting on agricultural land in the United States. Energy Research & Social Science. DOI:10.1016/j.erss.2022.102731

Moore, K. A. and D. B. Lobell. 2024. Opportunities and barriers for agrivoltaics on Tribal lands. Sustainability 16: 5414.

Mupambi, G., Anthony, B. M., Layne, D. R., Musacchi, S., Serra, S., Schmidt, T., and L. A. Kalcists. 2018. The Influence of Protective Netting on Tree Physiology and Fruit Quality of Apple: A Review. *Scientia Horticulturae* 236: 60–72. https://doi.org/10.1016/j.scienta.2018.03.014.

Mupambi, G., Sandler, H. A., and P. Jeranyama. 2021. Installation of an agrivoltaic system influences microclimatic conditions and leaf gas exchange in cranberry. Acta Horticulturae 1337, 117-124.

National Agricultural Statistics Service. 2024. Value of Washington's 2023 Agricultural Production Totaled a Record High of Nearly $14.0 Billion. USDA. https://www.nass.usda.gov/Statistics_by_State/Washington/Publications/Current_News_Release/2024/VOP_WA.pdf

Net-Zero Northwest. 2023. Technical and Economic Pathways to 2050. Technical Report. 06/21/23. Prepared by Evolved Energy Research.https://cdn.prod.website-files.com/64512dc345012a0e621f373f/655bd194fe78e74eabe87281_Evolved_NZNW_Energy_Technical%20Report_06-2023.pdf

Nikiema, P. M. E. 2023. Agrivoltaisme: etude de l'effect des panneaux photovoltaïques bifaciaux sur le cycle cultural de légumes sur la parcelle agroforestiere de wasabi. Thesis. Gembloux Agro-Bio Tech.

Oleskewicz, K. M. 2020. The effect of gap spacing between solar panel clusters on crop biomass yields, nutrients, and the microenvironment in a dual-agrivoltaic system. Thesis. University of Massachusetts Amherst.

Ong, S., Campbell, C., Denholm, P., Margolis, R., and G. Heath. 2013. Land-use requirements for solar power plants in the United States. National Renewable Energy Laboratory. NREL/TP-6A20-56290. https://docs.nrel.gov/docs/fy13osti/56290.pdf

Pandey, G., Lyden, S., Franklin, E., Millar, B., and M. T. Harrison. 2025. A systematic review of agrivoltaics: productivity, profitability, and environmental co-benefits. Sustainable Production and Consumption 56: 13-36.

Pascaris, A. S., Handler, R., Schelly, C., and J. M. Pearce. 2021. Life cycle assessment of pasture-based agrivoltaic systems: emissions and energy use of integrated rabbit production. Cleaner and Responsible Consumption 3: 100030.

Portner, S. L. 2023. Dair farm resiliency: automated milking, soil health, crossbreeding, and Agrivoltaics. Thesis. University of Minnesota.

Preston, S., Rajagopalan, K., Yourek, M., Kalcsits, L., and D. Singh. 2024. Changing climate risks for high-value tree fruit production across the United States. Environmental Research Letters 19: 124092.

Quarshie, P. K. 2023. Effect of photovoltaic panel shading on the growth of ginger and kale. Thesis. Ohio University.

Randle-Boggis, R. J., Barron-Gafford, G. A., Kimaro, A. A., Lamanna, C., Macharia, C., Maro, J., Mbele, A., and S. E. Hartley. 2025. Harvesting the sun twice: energy, food and water benefits from agrivoltaics in East Africa. Renewable and Sustainable Energy Reviews 208: 115066.

Ramasamy, V., Zuboy, J., Woodhouse, M., O'Shaughnessy, E., Feldman, D., Desai, J., Walker, A., Margolis, R., and P. Basore. 2023. U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, with Minimum Sustainable Price Analysis: Q1 2023. National Renewable Energy Laboratory. NREL/TP-7A40-87303. https://docs.nrel.gov/docs/fy23osti/87303.pdf

Reher, T., Willockx, Bisschop, J., Schenk, A., Nicolai, B., Cappelle, J., and B. Van de Poel. 2022. Pear harvest in an agrivoltaic cropping system: results from 2021 and future perspectives. AgriVoltaics 2022. Piacenza, Italy.

Reher, T., Willockx, B., Schenk, A., Bisschop, J., Huyghe, Y., Nicolai, B. M., Martnes, J. A., Diels, J., Cappelle, J., and B. Van de Poel. 2025. Agrivoltaic cultivation of pears under semi-transparent panels reduces yield consistently and maintains fruit quality in Belgium. Agronomy for Sustainable Development 45: 25.

Rogers, M. A. 2022. Consumer study of agrivoltaics food products including tomato, basil, potato, bean, and squash. [Master's thesis, University of Arizona, Tucson, USA].

Scarano, A., Semeraro, T., Calisi, A., Aretano, R., Rotolo, C., Lenucci, M. S., Santino, A., Piro, G., and M. De Caroli. 2024. Effects of the agrivoltaic system on crop production: the case of tomato (*Solanum lycopersicum* L.). Applied Sciences 14: 3095.

Schick, T. and M. Samayoa. 2025. Liberal Oregon and Washington vowed to pioneer green energy. Almost every other state is beating them. ProPublica. 12 May 2025. https://www.propublica.org/article/oregon-washington-green-energy-bonneville

Seel, J., Kemp, J. M., Cheyette, A., Millstein, D., Gorman, W., Jeong, S., Robson, D., Setiawan, R., and M. Bolinger. 2024. Utility-Scale Solar, 2024 Edition. *Lawrence Berkeley National Laboratory*, Utility-Scale Solar, October.

Setyorini, T., Wijayanti, Y., Nurrohim, A., Subandriya, A., Prasetya, R. B., Murhuda, M., and B. Wibawa. 2024. Mustard (*Brassica rapa*) and eggplants (*Solanum melongena*) cultivation in agrivoltaic system in coastal area, case study of Baron Technopark, Yogyakarta. Juatika. Jurnal Agronomi Tanaman Tropika 6. DOI:10.36378/juatika.v6i2.3570

Sharpe, K. T. 2020. Electrical consumption on Midwestern dairy farms in the United States and agrivoltaics to shade cows in a pasture-based dairy system. Thesis. University of Minnesota.

Sharpe, K. T., Heins, B. J., Buchanan, E. S., and M. H. Reese. 2021. Evaluation of solar photovoltaic systems to shade cows in a pasture-based dairy herd. Journal of Dairy Science 104: 2794-2806.

Simmons, S., Morrissey, T., Kennedy, J. 2025. 9th Power Plan Demand Forecast. Northwest Power and Conservation Council. https://www.nwcouncil.org/fs/19380/2025_0429_2.pdf

Singh, R., Scalisi, A., McClymont, L., and I. Goodwin. 2023. Effects of above-canopy photovoltaic arrays on crop yield and fruit quality in a pear orchard. Acta Horticulturae 1403. DOI:10.17660/ActaHortic.2024.1403.34

Smith, V. M. 2025. Balancing agriculture and solar energy systems: local government strategies for permitting agrivoltaics under Washington's Growth Management Act. Capstone. University of Washington, Master of Infrastructure Planning and Management.

Stewart, W. C., Scasta, J. D., Maierle, C., Ates, S., Burke, J. M., and B. J. Campbell. 2025. Vegetation management utilizing sheep grazing within utility-scale solar: agro-ecological insights and existing knowledge gaps in the United States. Small Ruminant Research 243: 107439.

Stid, J. T., Shukla, S., Kendall, A. D., Anctil, A., Hyndman, D. W., Rapp, J., and R. P. Anex. 2025. Impacts of agrisolar co-location on the food-energy-water nexus and economic security. Nature Sustainability. DOI:10.1038/s41893-025-01546-4

Strub, L., Wittke, M., Trommsdorff, M., Stoll, M., Kammann, C., and S. Loose. 2024. Assessing the economic performance of agrivoltaic systems in vineyards – framework development, simulated scenarios and directions for future research. Frontiers in Horticulture 3: 1473072.

Sturchio, M. A., Kannenberg, S. A., and A. K. Knapp. 2024. Agrivoltaic arrays can maintain semi-arid grassland productivity and extend the seasonality of forage quality. Applied Energy 356: 122418.

Swanson, T., Seay-Fleming, C., Gerlak, A. K., and G. A. Barron-Gafford. 2025. "Enough is enough, we like our farms": the role of landscape ideology in shaping perceptions of solar energy and agrivoltaics in the rural American Southwest. Journal of Rural Studies 114: 103572.

Tajima, M. and T. Iida. 2021. Evolution of agrivoltaic farms in Japan. AIP Conference Proceedings 2361: 030002. DOI:10.1063/5.0054674

Tang, Y., Ma, X., Li, M., and Y. Wang. 2020. The Effect of Temperature and Light on Strawberry Production in a Solar Greenhouse. *Solar Energy* 195 (January):318–28. https://doi.org/10.1016/j.solener.2019.11.070.

The World Bank. 2020. Global photovoltaic power potential by country. Energy Sector Management Assistance Program. https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf

Trommsdorff, M., Dhal, I. Sw., Ozdemir, O. E., Ketzer, D., Weinberger, N., and C. Rosch. 2022. Chapter 5. Agrivoltaics: solar power generation and food production. In Solar Energy Advancements in Agriculture and Food Production Systems. DOI:10.1016/B978-0-323-89866-9.00012-2

Trommsdorff, M., Hopf, M., Hornle, O., Berwind, M., Schindele, S., and K. Wydra. 2023. Can synergies in agriculture through an integration of solar energy reduce the cost of agrivoltaics? An economic analysis in apple farming. Applied Energy 350: 121619.

USDA. 2024. 2024 State Agriculture Overview. Washington. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=WASHINGTON

Vaughan, A., Brent, A., Fitzgerald, M., and J. Kueppers. 2023. Agrivoltaics: Integrating solar energy generation with livestock farming in Canterbury. Prepared for: Our Land Water Rural Professionals Fund 2023.

Vaughan, A. and A. Brent. 2024. Agrivoltaics for small ruminants: a review. Small ruminant research 241: 107393.

Velez, S., Bretzel, T., Poter, R., Berwind, M. F., and M. Trommsdorff. 2025. PREPRINT. Iot-based monitoring of overhead agrivoltaic systems to analyze the delay in apple ripening and its influence on maturation patterns. Available at SSRN. DOI:10.2139/ssrn.510506

Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., and P. Högy. 2019. Agrophotovoltaic Systems: Applications, Challenges, and Opportunities. A Review. *Agronomy for Sustainable Development* 39 (4): 35. https://doi.org/10.1007/s13593-019-0581-3.

Widmer, J., Christ, B., Grenz, J., and L. Norgrove. 2024. Agrivoltaics, a promising new tool for electricity and food production: a systematic review. Renewable and Sustainable Energy Reviews 192: 114277.

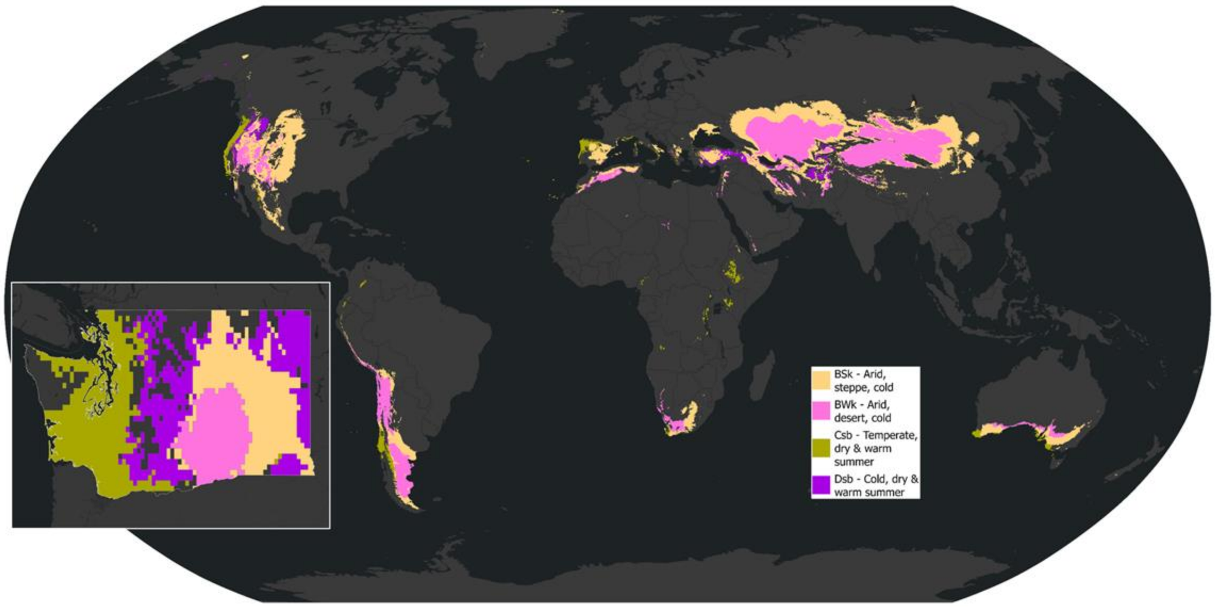
Willockx, B., Reher, T., Lavaert, C., Herteleer, B., Van de Poel, B., and J. Cappelle. 2024. Design and evaluation of an agrivoltaic system for a pear orchard. Applied Energy 353: 122166.

Wiseman, H. J., Wiseman, S. R., and C. Wright 2023. Farming solar on the margins. Boston University Law Review 103: 525.

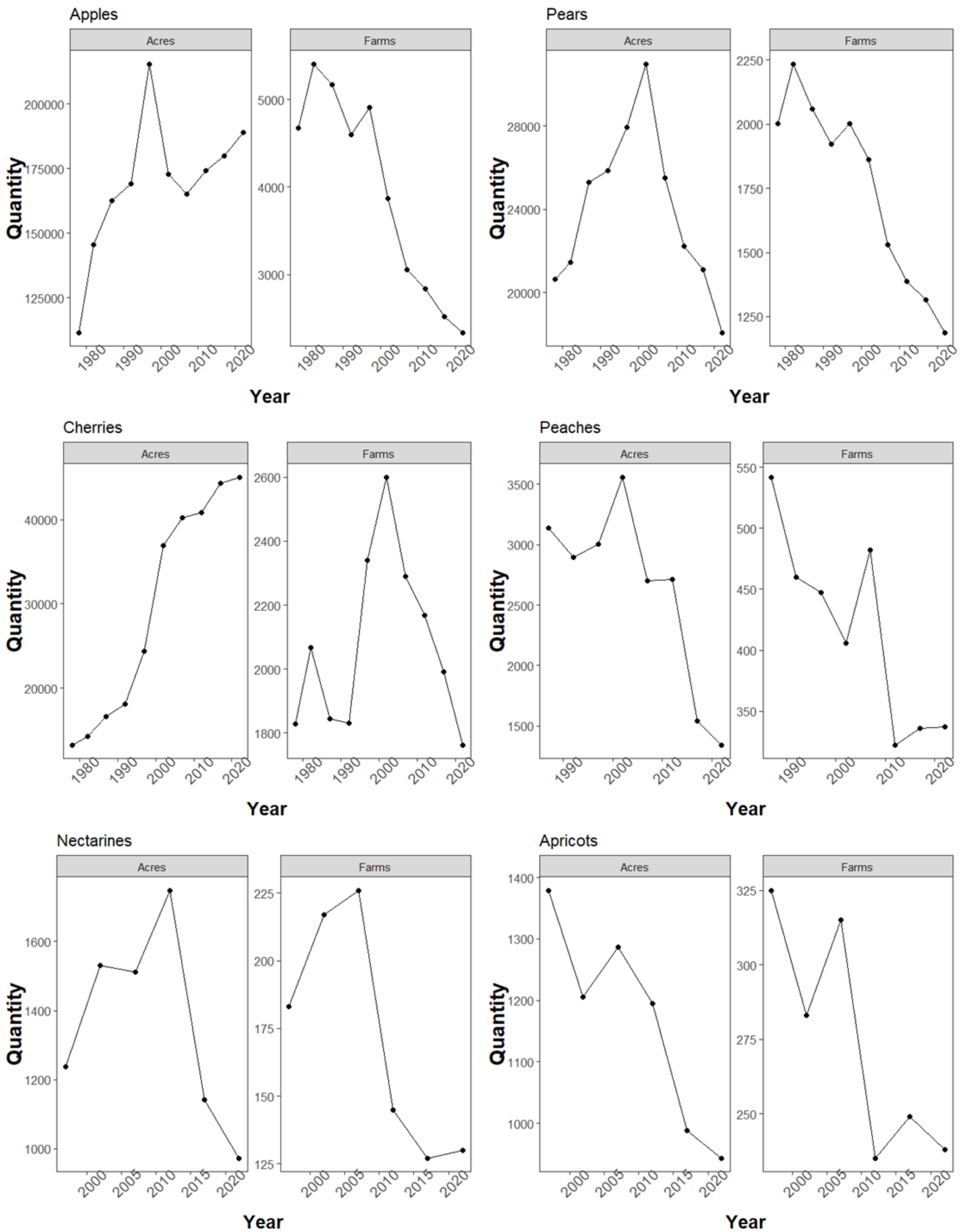
Zheng, J., Meng, S., Zhang, X., Zhao, H., Ning, X., Chen, F., Omer, A. A. A., Ingenhoff, J., and W. Liu. 2021. Increasing the comprehensive economic benefits of farmland with Even-lighting Agrivoltaic Systems. PLoS ONE 16: e0254482

Zhou, A. 2025. WA ranchers turn to new crop: solar power. Seattle Times. 09 March 2025. https://www.seattletimes.com/seattle-news/climate-lab/wa-ranchers-turn-to-new-crop-solar-power/

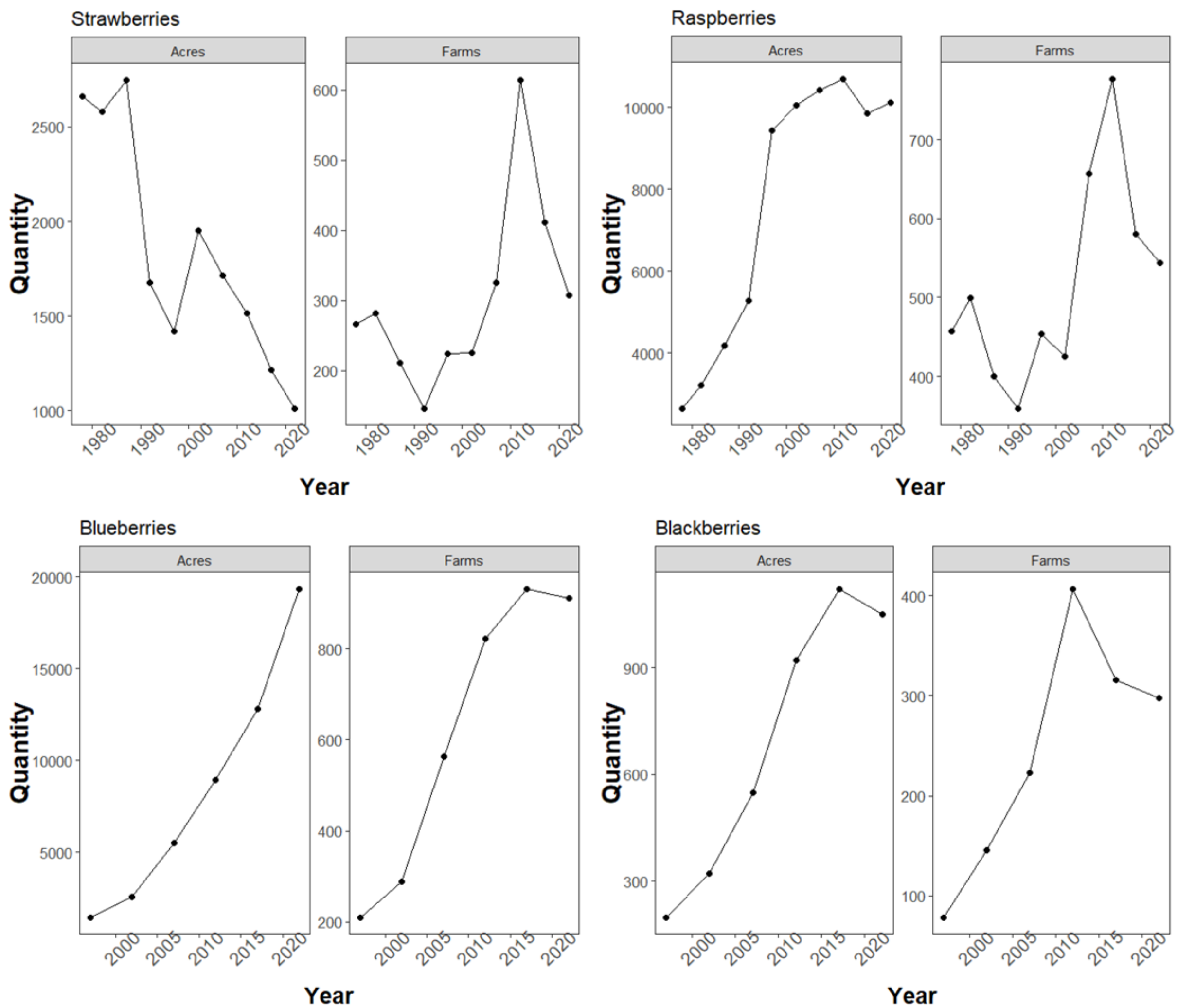
Appendixes



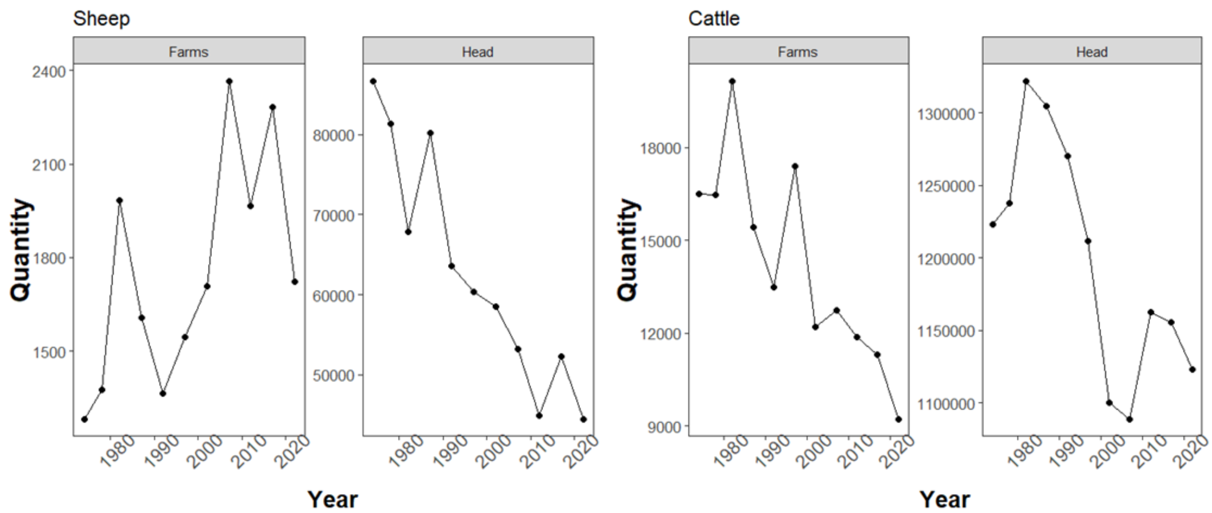
Appendix Figure 50. The global distribution of the four Koppen-Geiger climate classes relevant to Washington's agricultural regions. Washington and its climate classes are inset.



Appendix Figure 51. Trends in different tree fruit acreage and farm numbers over time. Crops like apples and cherries show increasing acreage and decreasing numbers of total farms, indicative of consolidation. Other tree fruit varieties show a decline in both acreage and farms. Data were aggregated from USDA Census of Agriculture reports. Note that data series begin in different years depending on the crop type.



Appendix Figure 52. Trends in different berry acreage and farm numbers over time. Although strawberry acreage has declined, other berries have increased in acreage over time. Data were aggregated from USDA Census of Agriculture reports. Note that data series begin in different years depending on the crop type.



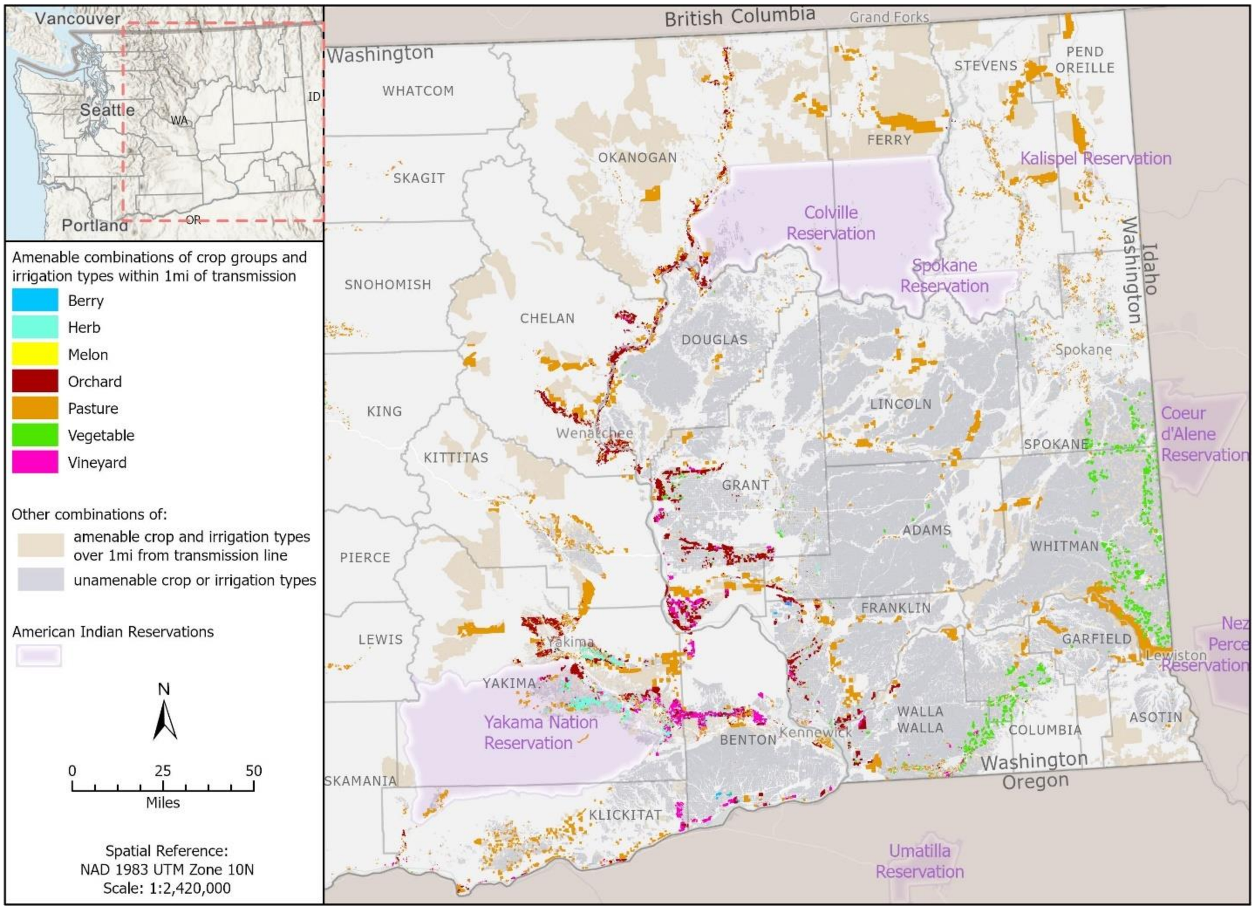
Appendix Figure 53. Trends in sheep and cattle farm numbers and head over time. Although the number of sheep have declined consistently for decades, there are an increasing number of sheep farms. Cattle farms and head have both been in decline. Data were aggregated from USDA Census of Agriculture reports

Appendix Table 1. Within 1-mile of transmission, the acreage of potential agrivoltaic land by crop group and either side of Washington

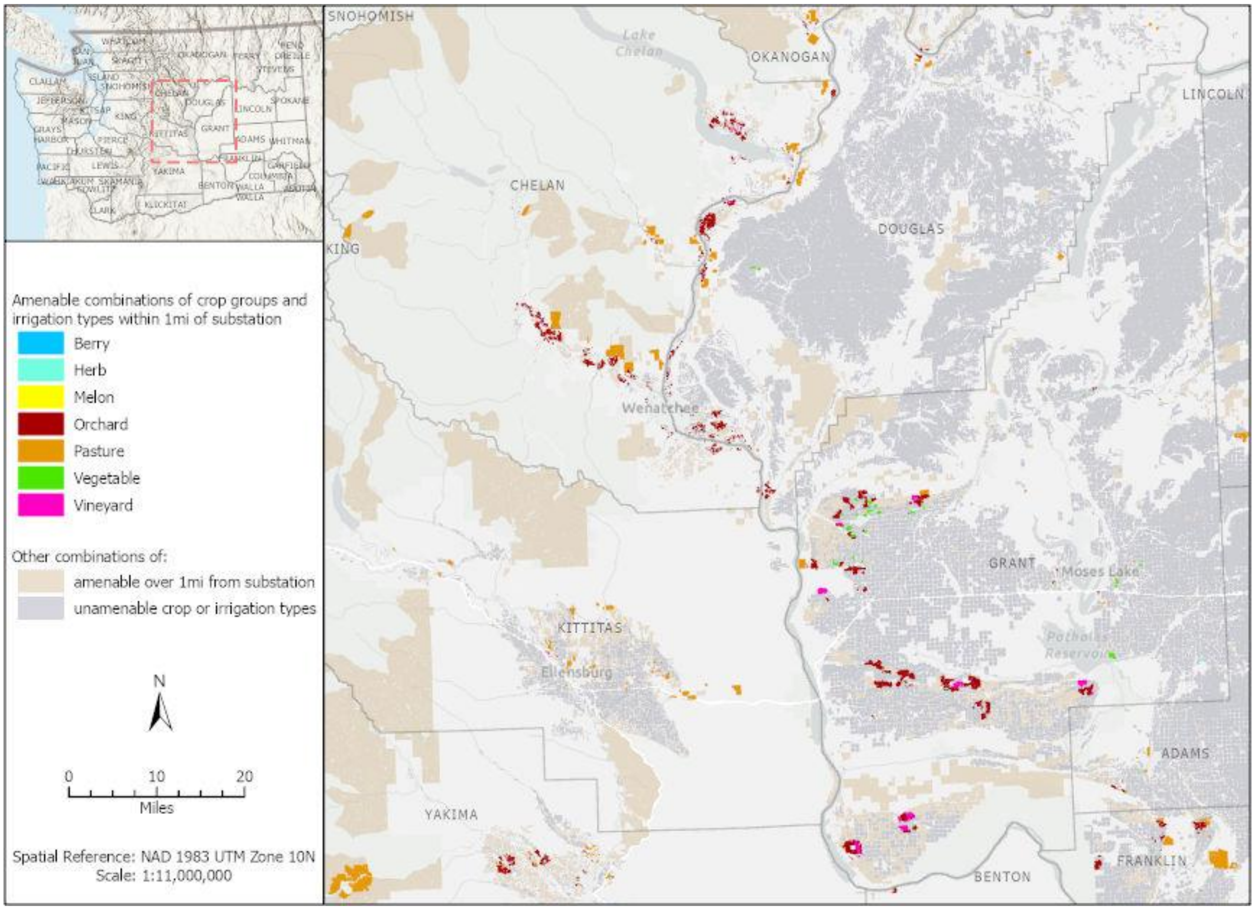
	Crop Group	Acreage	Energy Capacity (GW)
Central & Eastern Washington	Berry	3,985	0.4-0.8
	Herb	27,200	2.7-5.4
	Orchard	145,762	14.6-29.2
	Pasture	527,004 (26,350)	52.7-105.4 (2.5-5.3)
	Vegetable	82,059	8.2-16.4
	Vineyard	41,927	4.2-8.4
Western Washington	Berry	13,313	1.3-2.7
	Herb	15	~0
	Orchard	694	~0.1
	Pasture	94,582 (4,729)	9.5-18.9 (0.5-0.9)
	Vegetable	5111	0.5-1.0
	Vineyard	360	0-0.1

*Numbers in parentheses reflect a re-analysis assuming a maximum of 5% of pastureland will be used for solar grazing

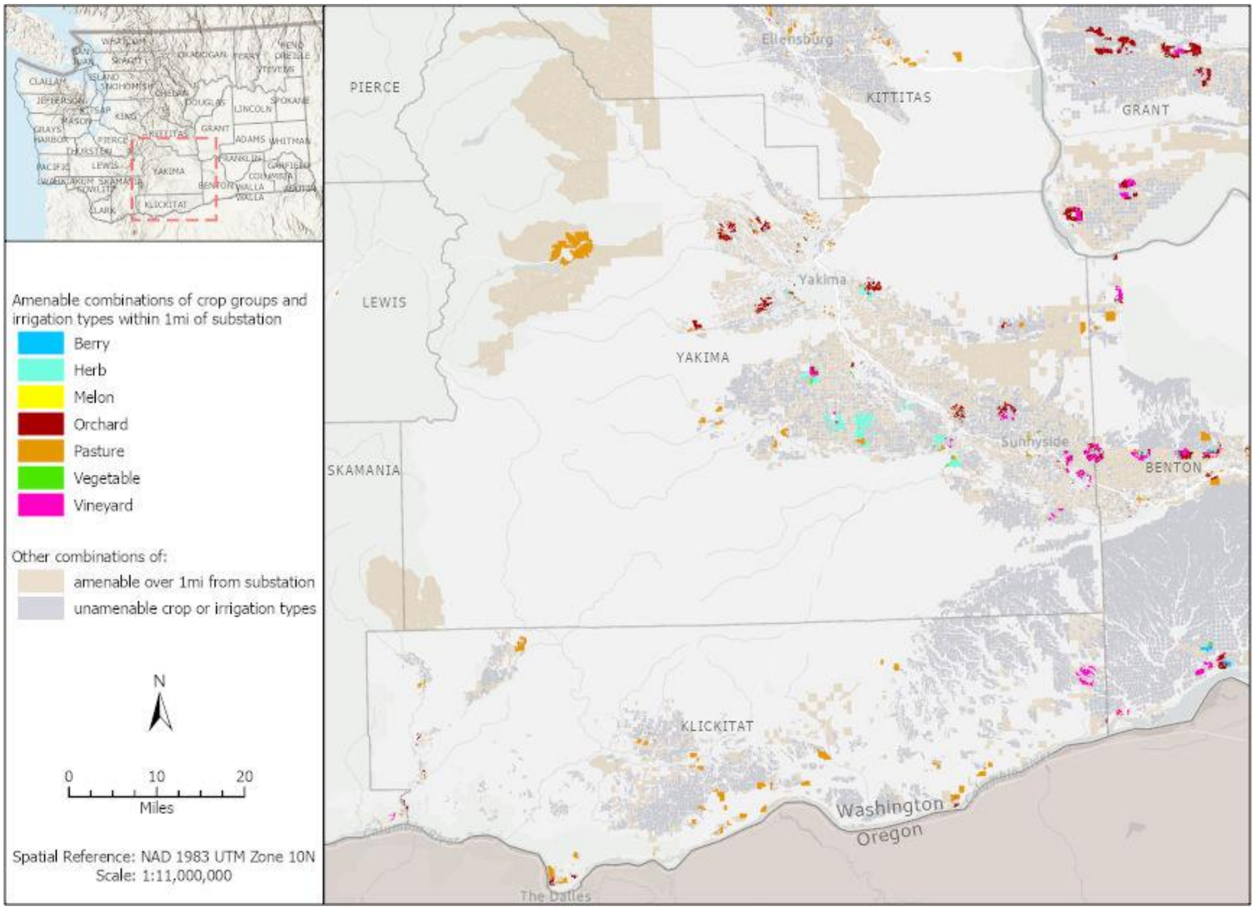
**Energy capacity is estimated based on an assumed 5-10 acres / MW needed for solar arrays based on NREL data



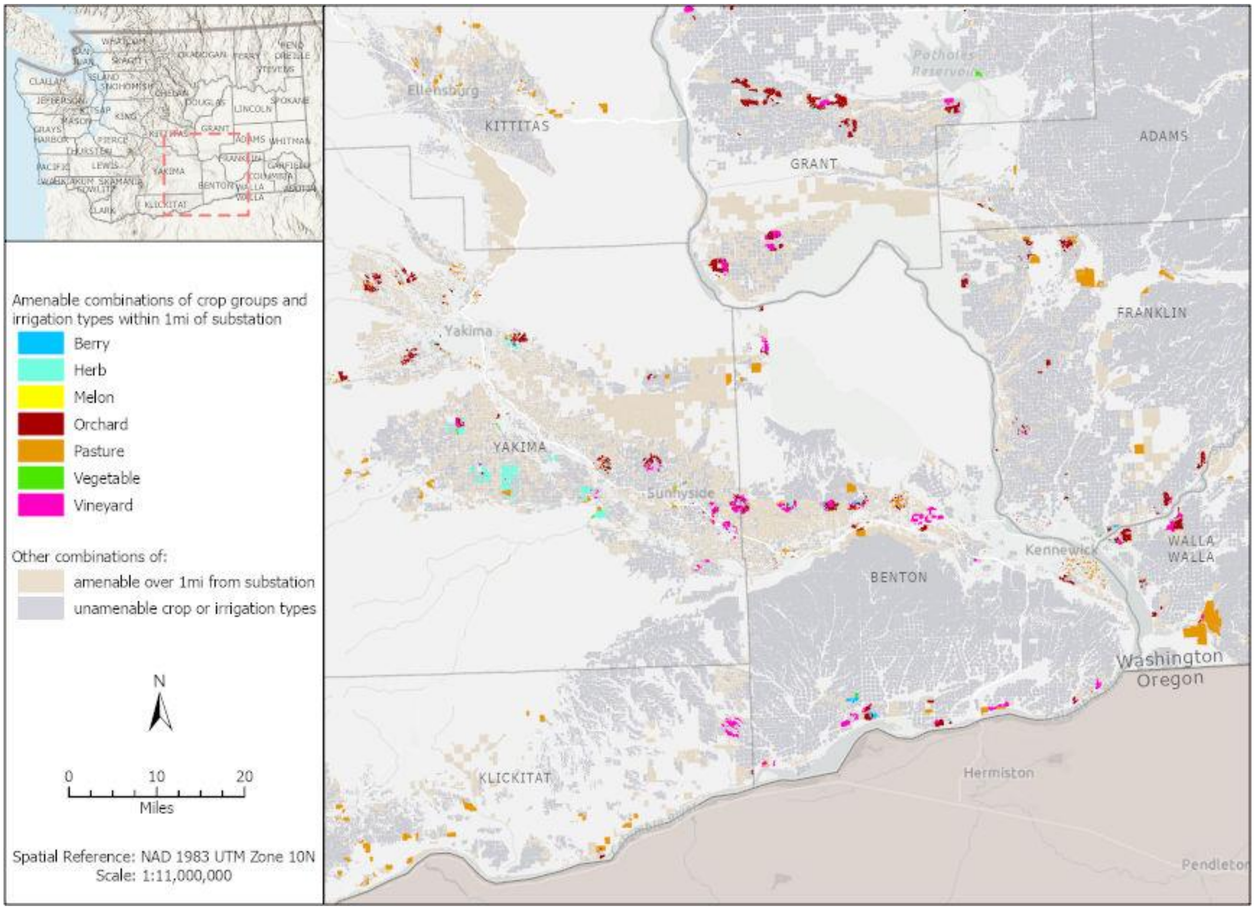
Appendix Figure 54 Agrivoltaic land potential occurs primarily in central and eastern Washington. Colored farm fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and which is within 1-mile of transmission. Gray farmland represents either crop types that are not amenable for agrivoltaics and/or farmland with high intensity irrigation infrastructure that restrict agrivoltaics. Tan farmland represents crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from transmission.



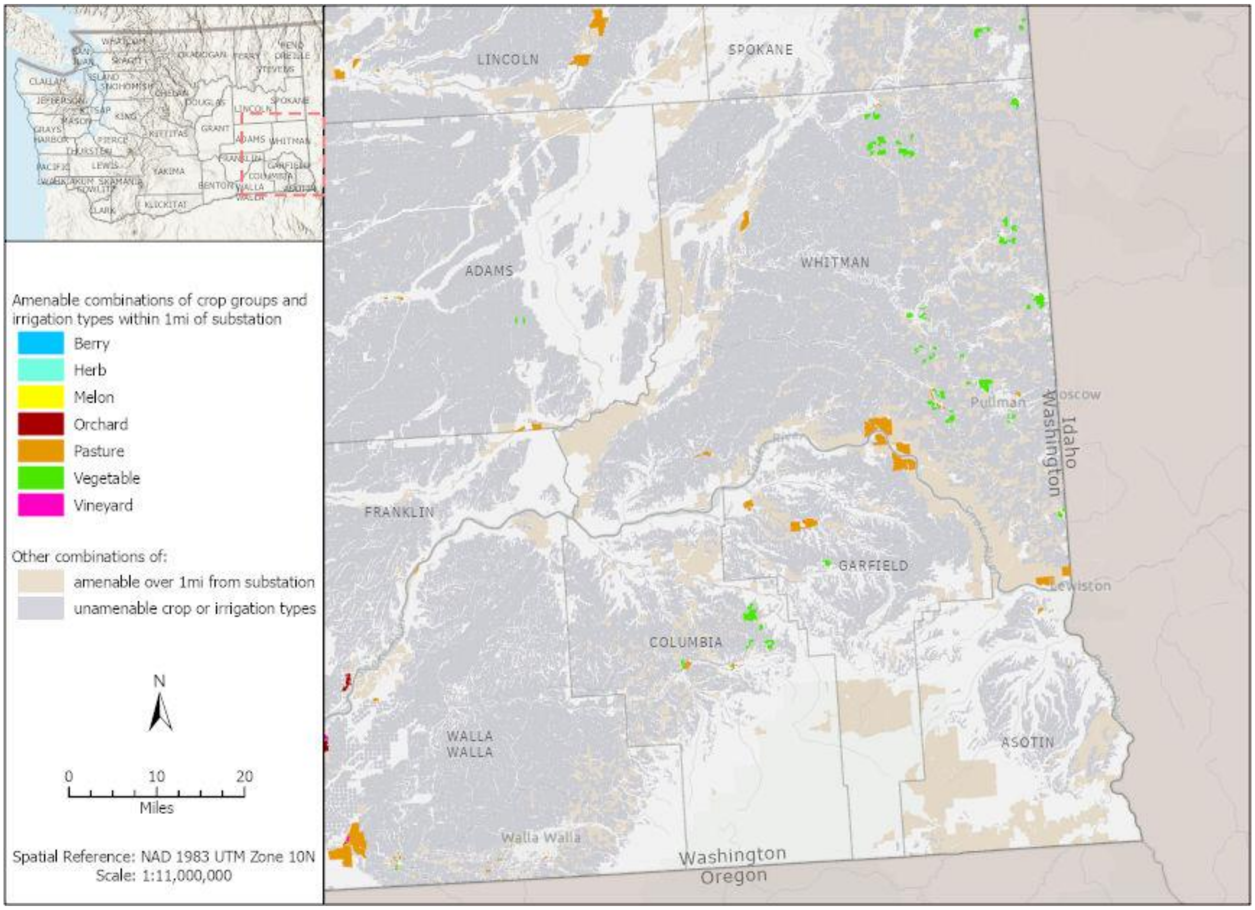
Appendix Figure 55. Potential agrivoltaic landscape in Kittitas and Grant counties as well as parts of Chelan and Douglas counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



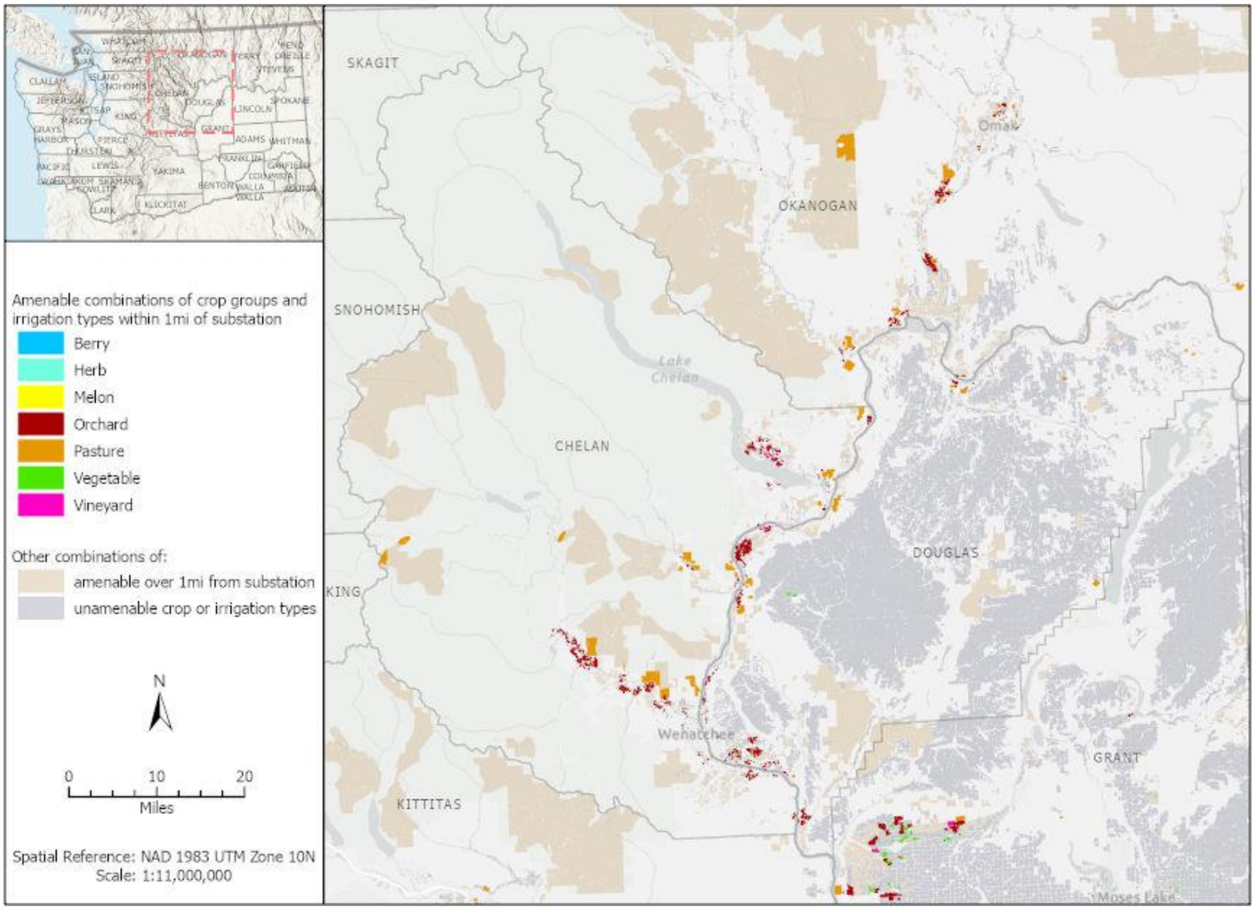
Appendix Figure 56. Potential agrivoltaic landscape in Yakima and Klickitat counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



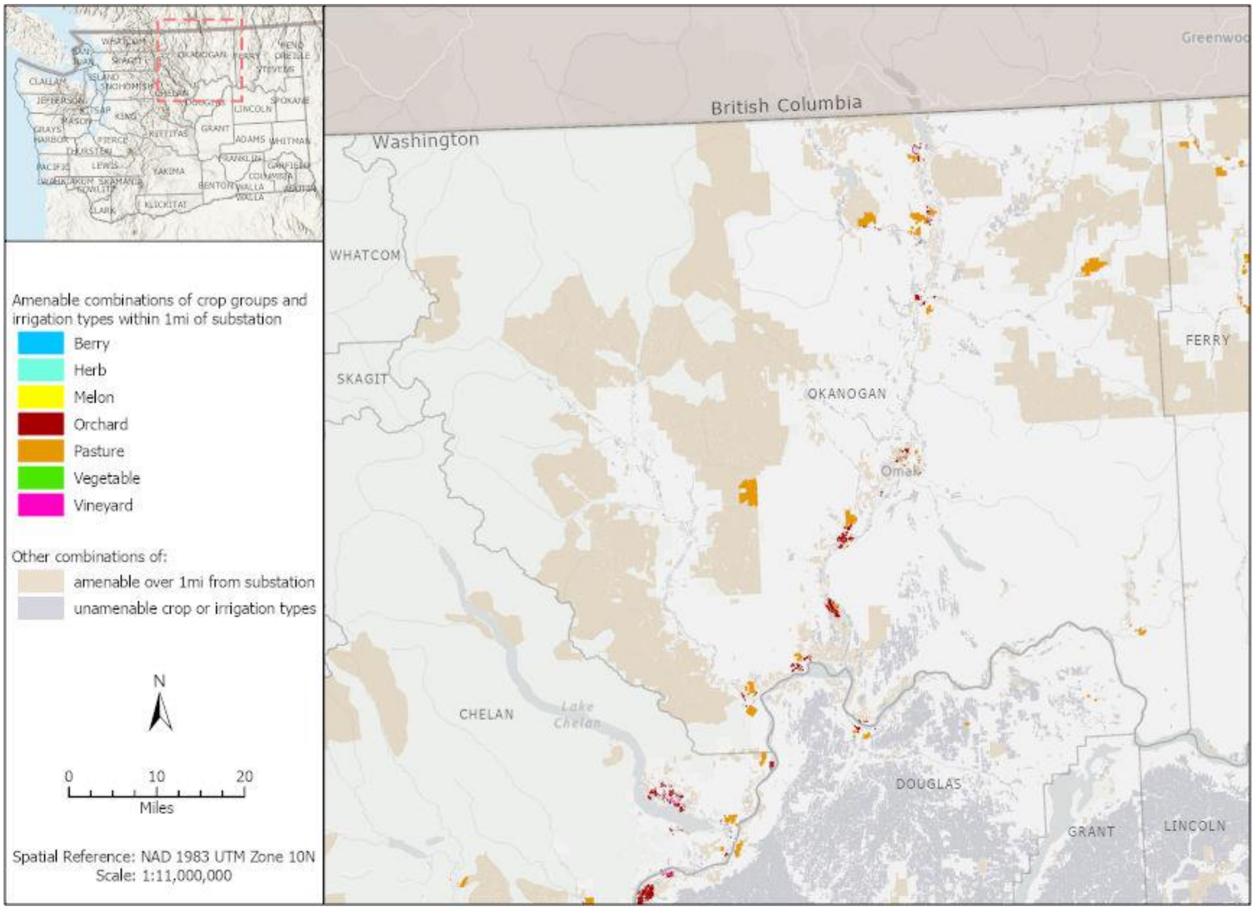
Appendix Figure 57. Potential agrivoltaic landscape in Benton County as well as parts of Kittitas, Walla Walla, Franklin, and Adams counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



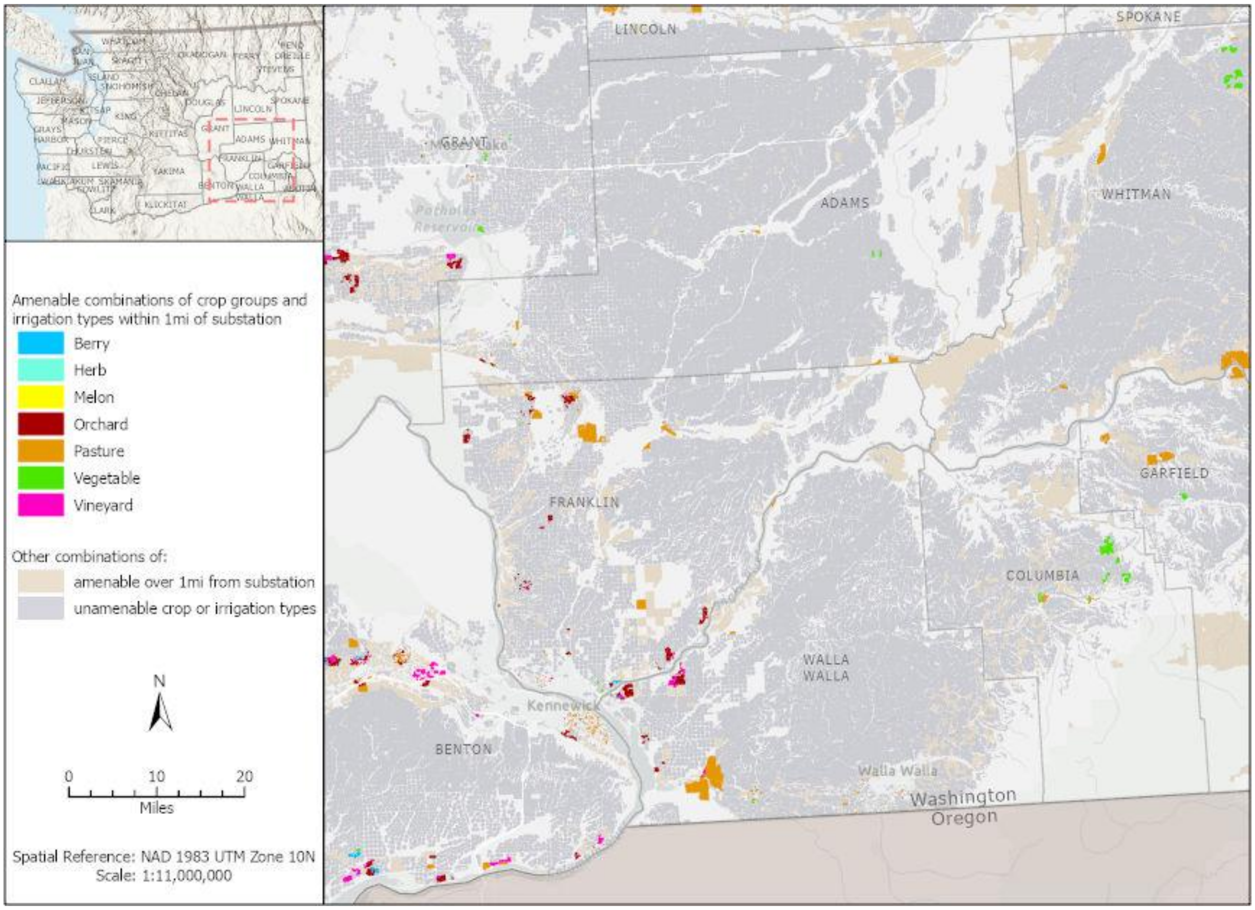
Appendix Figure 58. Potential agrivoltaic landscape in Whitman, Columbia, Garfield, and Asotin countiess. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations. We encourage caution when interpreting 'vegetable' as WSDA's data are likely including crops like legumes that may not be amenable for agrivoltaics.



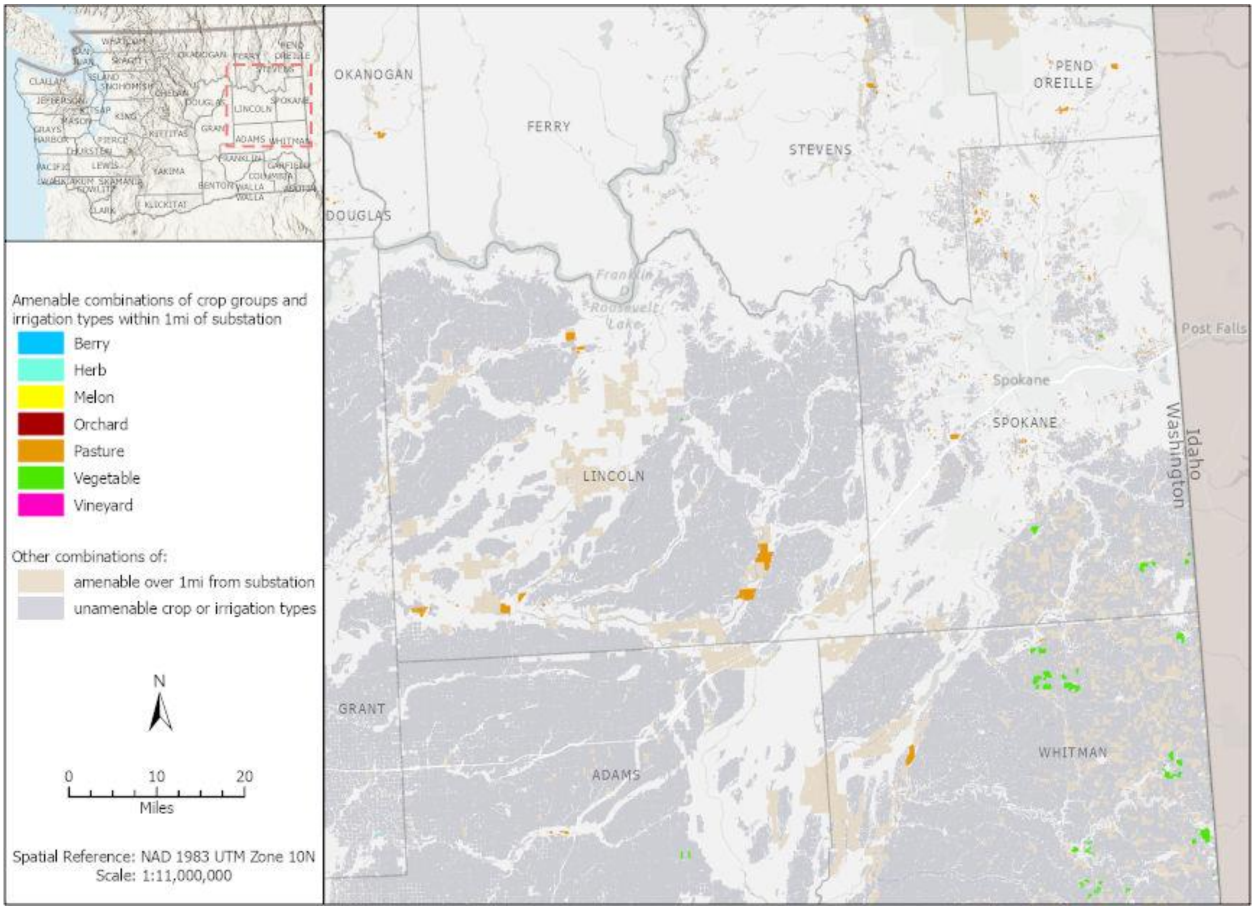
Appendix Figure 59. Potential agrivoltaic landscape in Chelan and Douglas counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



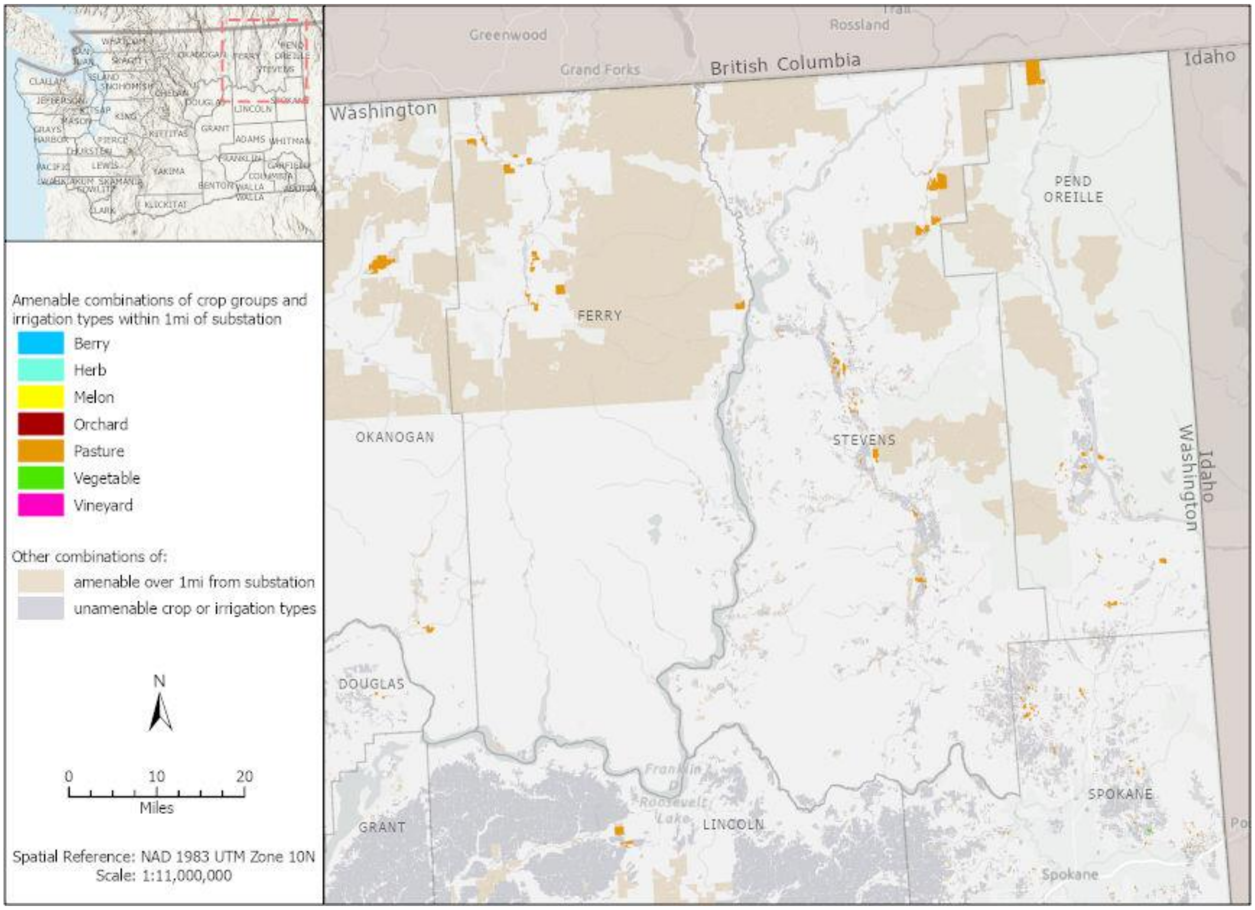
Appendix Figure 60. Potential agrivoltaic landscape in Okanogan County. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



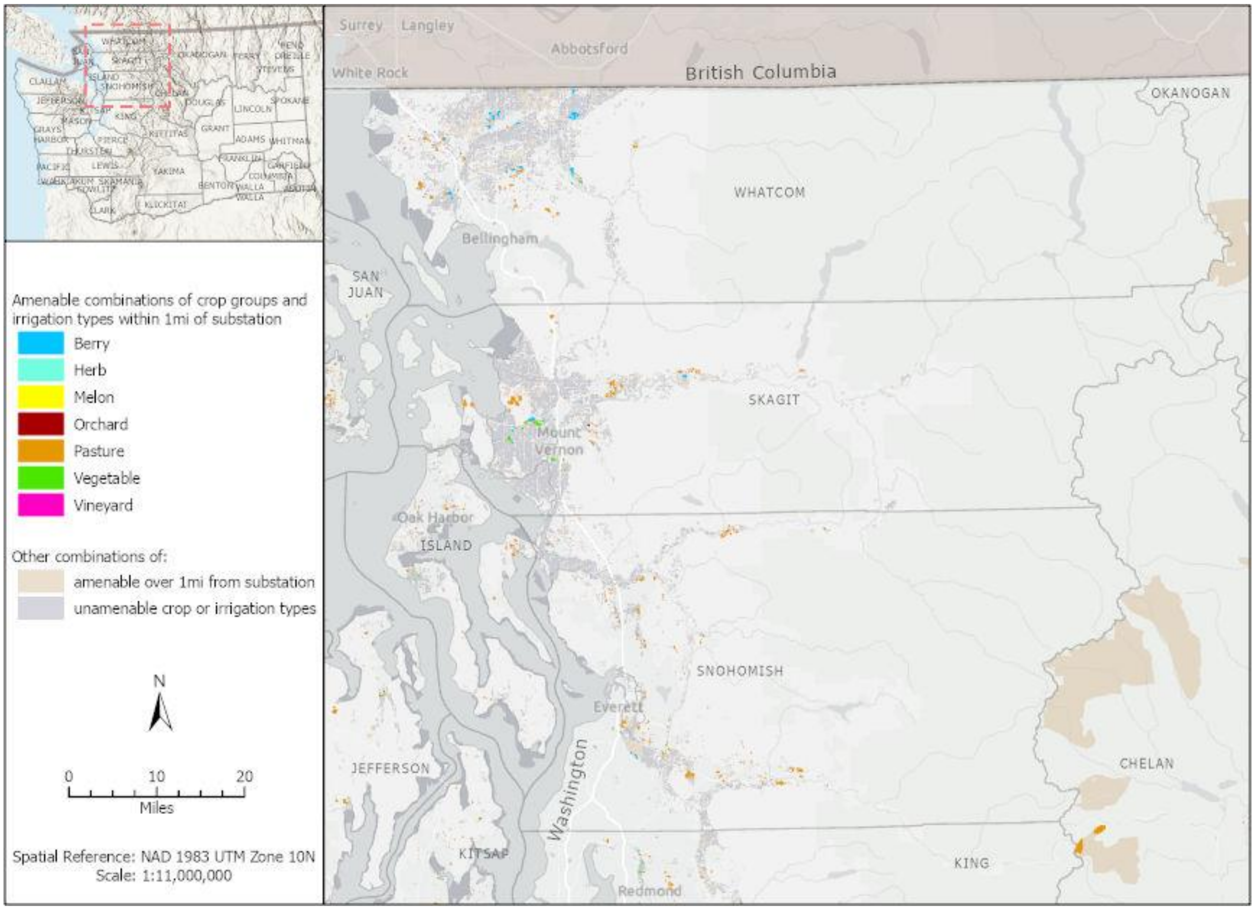
Appendix Figure 61. Potential agrivoltaic landscape in Adams and Franklin counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



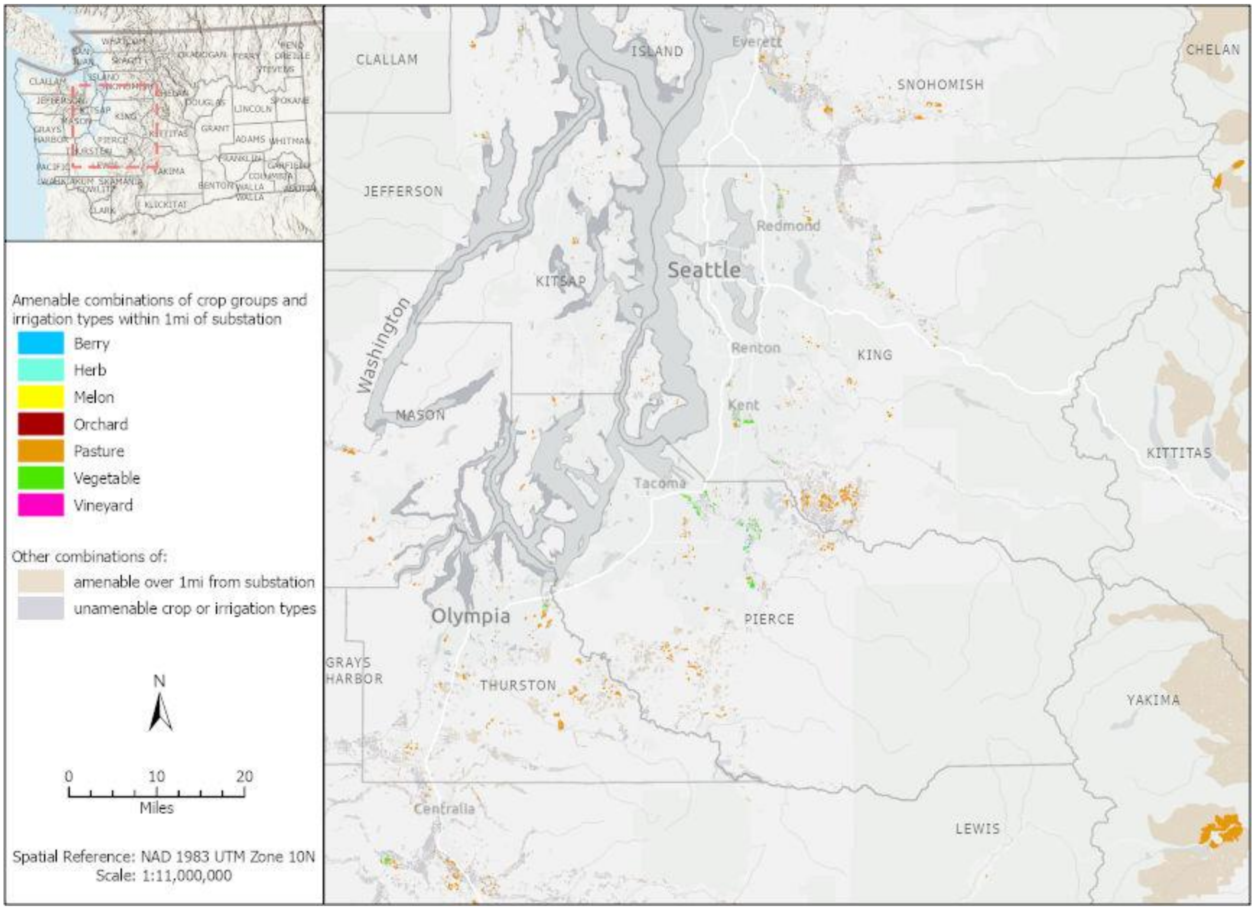
Appendix Figure 62. Potential agrivoltaic landscape in Lincoln and Spokane counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



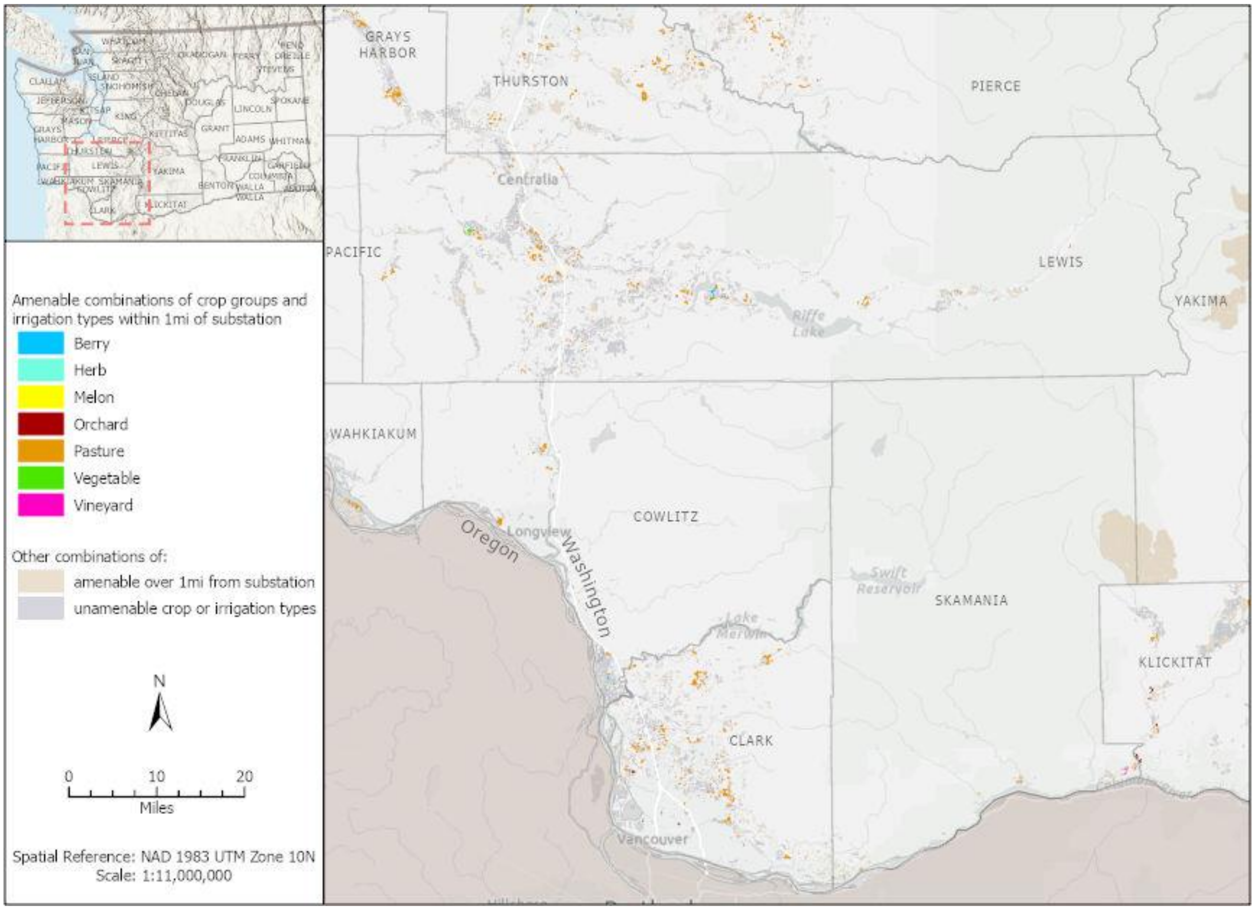
Appendix Figure 63. Potential agrivoltaic landscape in Ferry, Stevens, and Pend Oreille counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



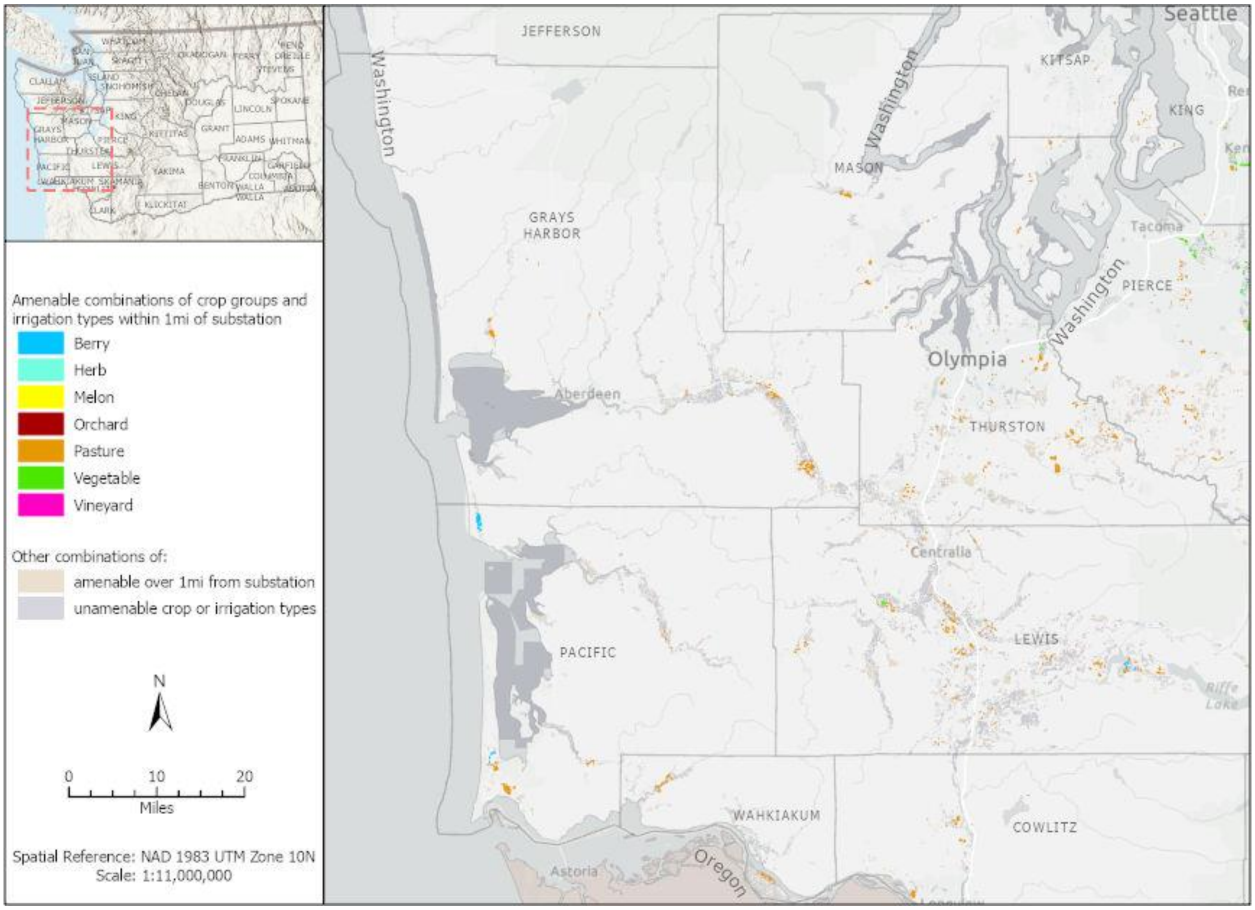
Appendix Figure 64. Potential agrivoltaic landscape in Whatcom, Skagit, Island, and Snohomish counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



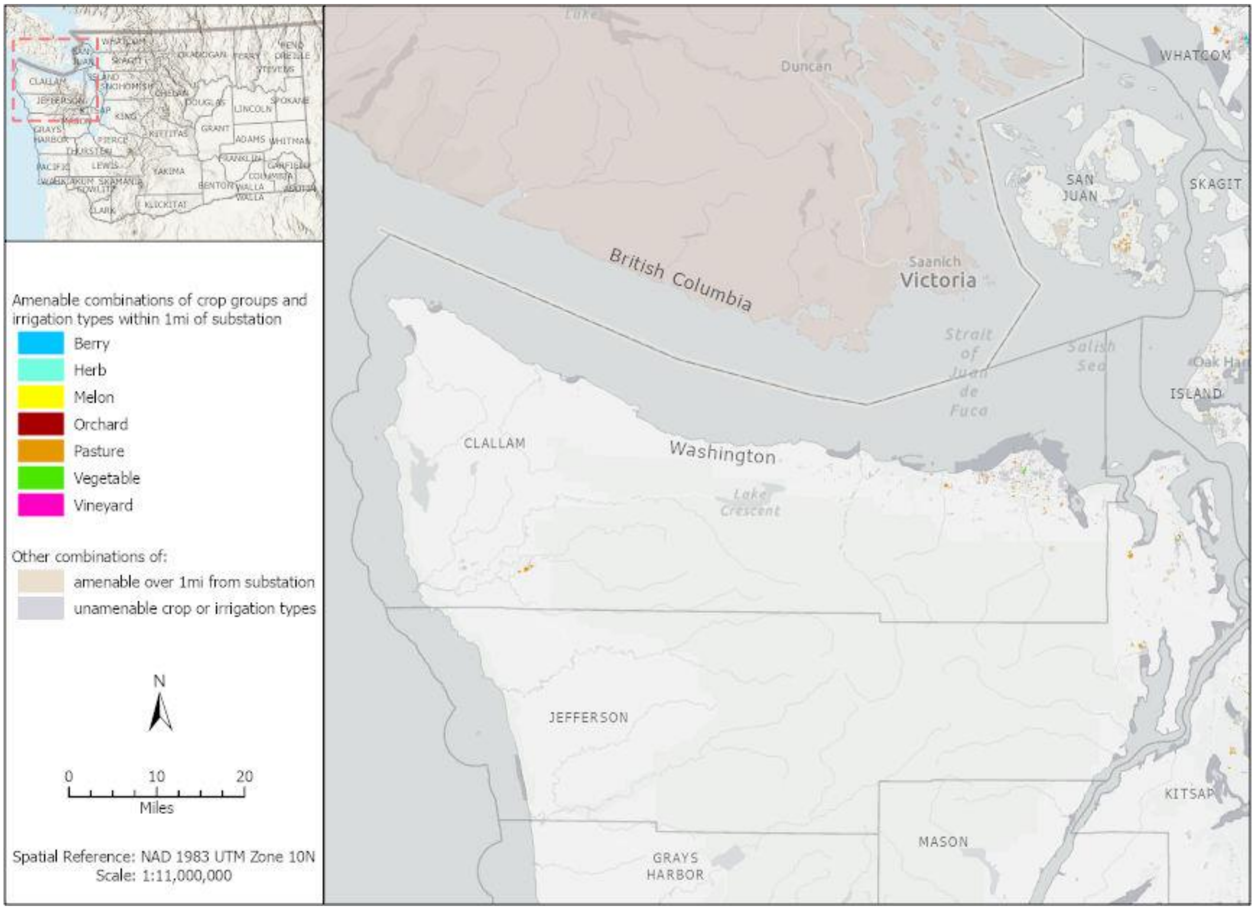
Appendix Figure 65. Potential agrivoltaic landscape in King, Pierce, Kitsap, and Thurston counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



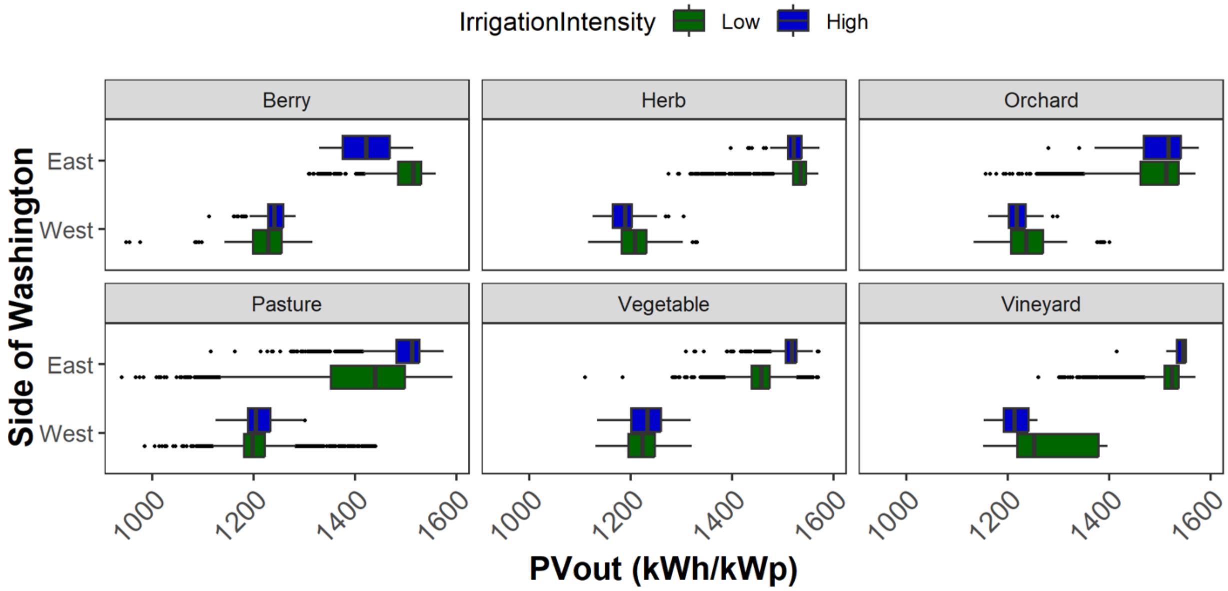
Appendix Figure 66. Potential agrivoltaic landscape in Lewis, Cowlitz, and Skamania counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



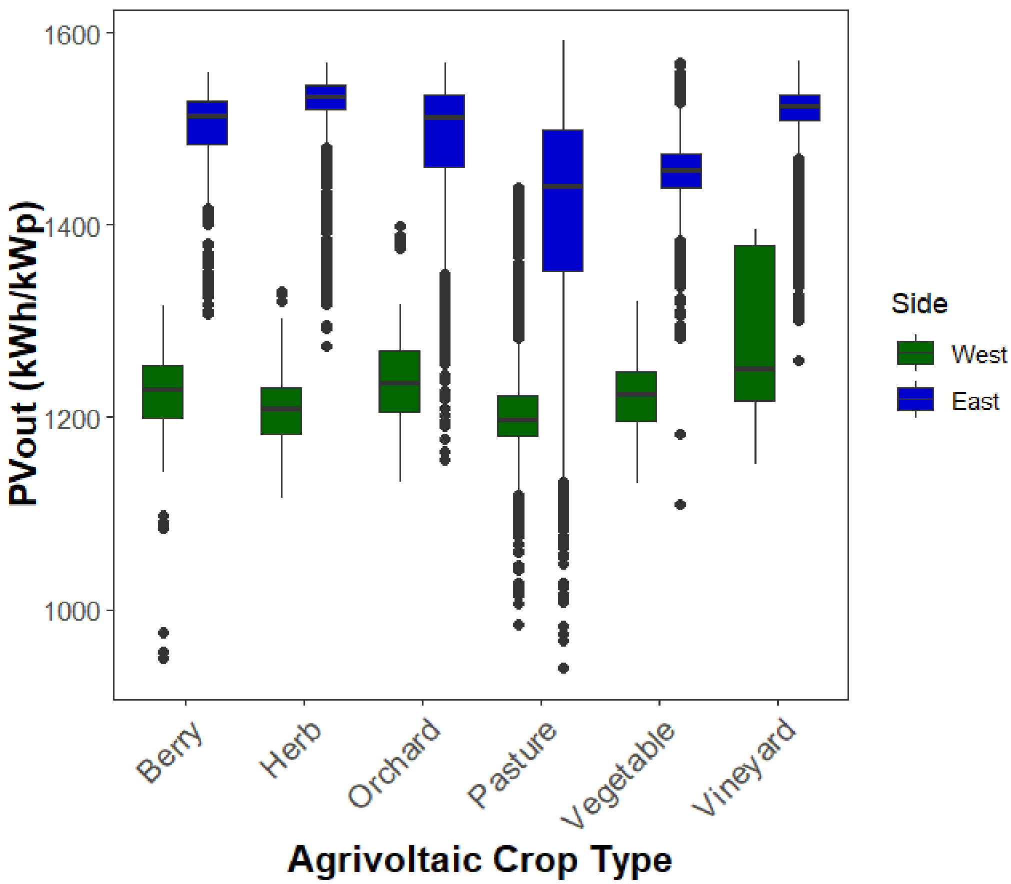
Appendix Figure 67. Potential agrivoltaic landscape in Grays Harbor, Pacific, Wahkiakum, Thurston, Lewis, and Mason counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



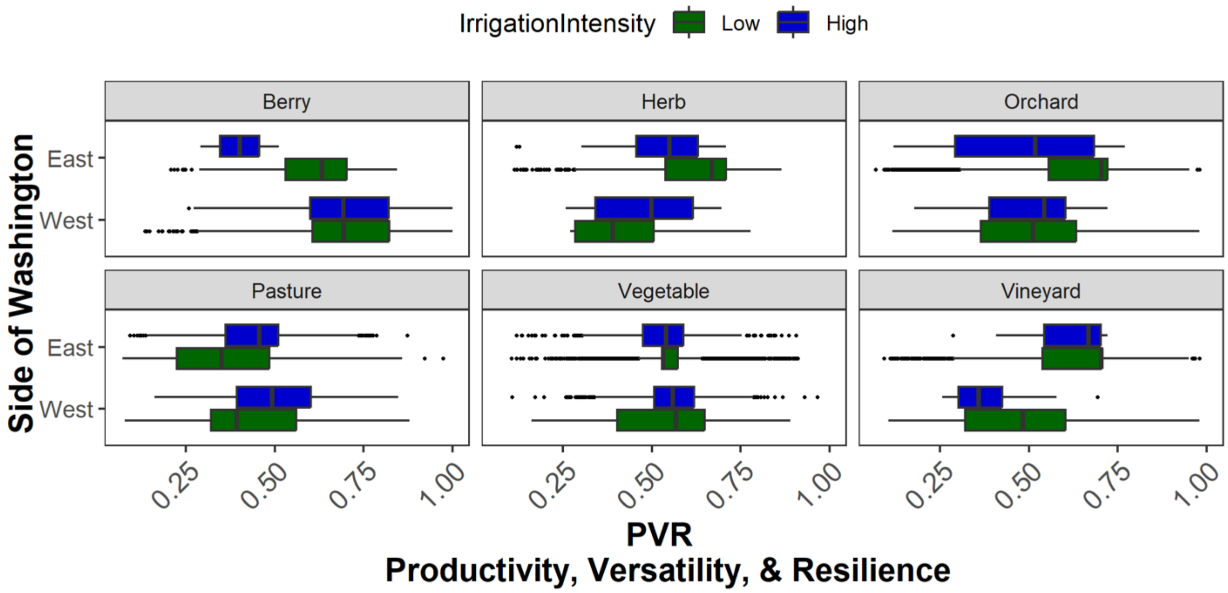
Appendix Figure 68. Potential agrivoltaic landscape in San Juan, Clallam, and Jefferson counties. Colored fields indicate farmland that has a crop type that is amenable to agrivoltaics, has lower intensity irrigation infrastructure, and is within 1-mile of a substation. Gray farm fields represent either crop types that are not amenable for agrivoltaics and/or farmland with high irrigation intensity that restrict agrivoltaics. Tan farm fields represent crop types that are hypothetically amenable to agrivoltaics but which are further than 1-mile from substations.



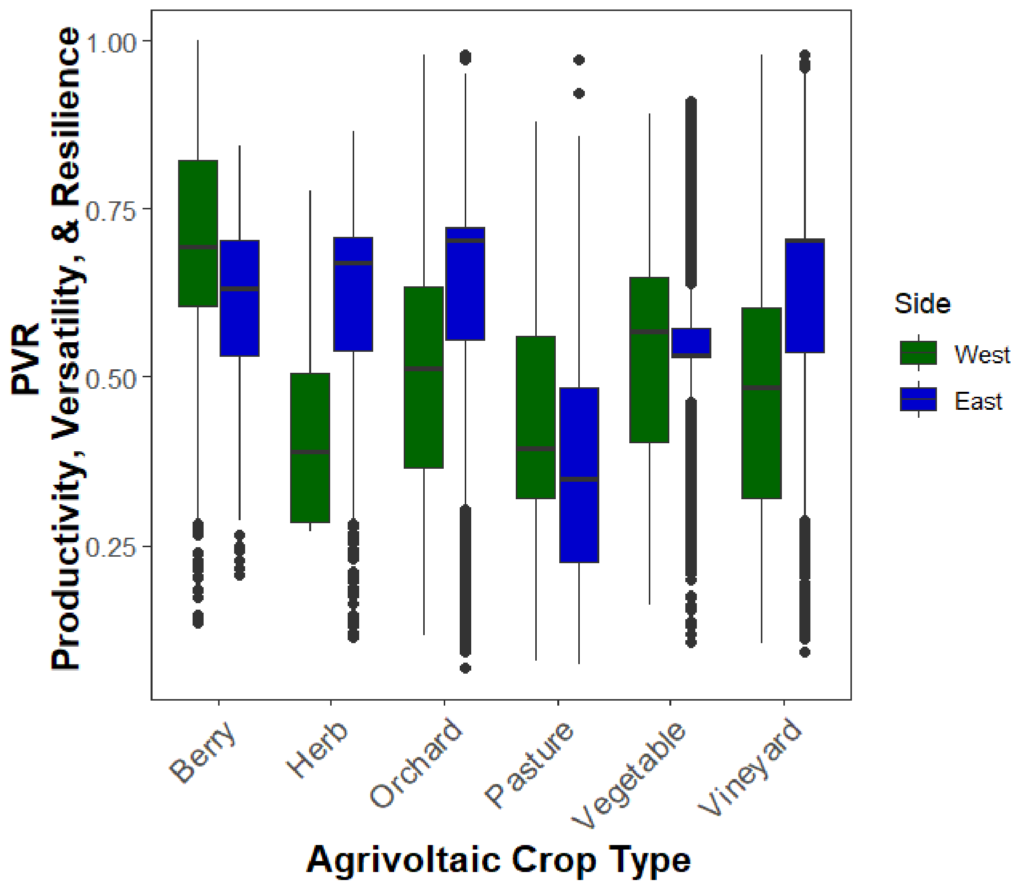
Appendix Figure 69. Boxplots showing the distribution of solar energy generation potential (PVout) as a function of low and high irrigation intensity farmland, different crop types that are amenable for agrivoltaics, and whether farmland is in eastern or western Washington. Each box's center line is the median value, lower and upper ends of the boxplots are the 25th and 75th percentiles of the data, the two horizontal lines represent the lower and upper bounds of most of the data, and the dots are outliers.



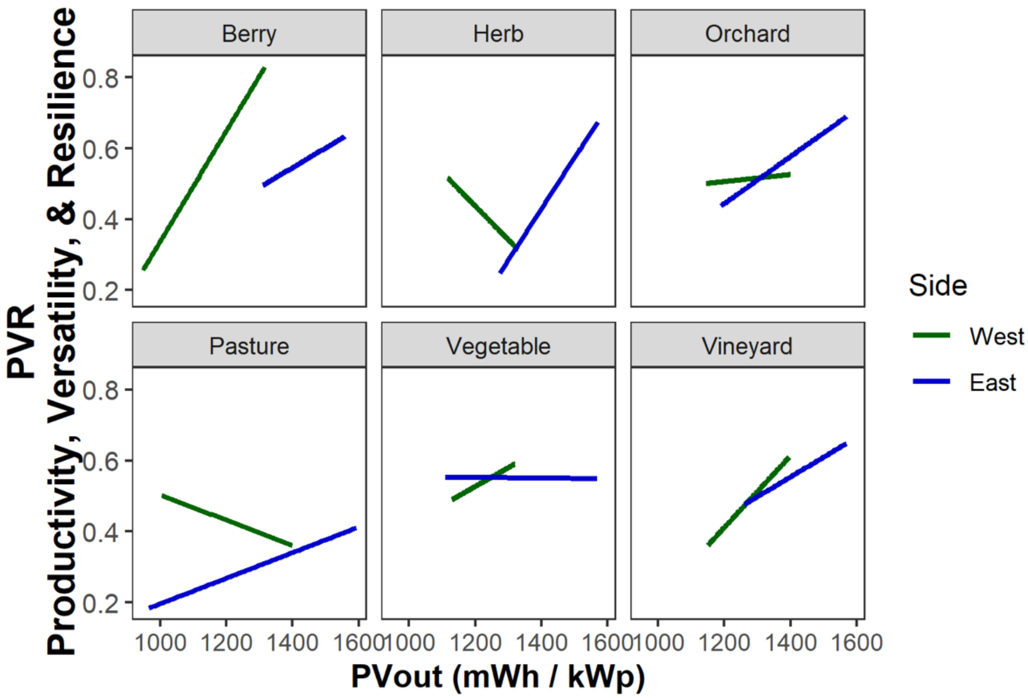
Appendix Figure 70. Boxplots showing the distribution of solar energy generation potential (PVout) as a function of different crop types that are amenable for agrivoltaics and whether farmland is in eastern or western Washington. Each box's center line is the median value, lower and upper ends of the boxplots are the 25th and 75th percentiles of the data, the two vertical lines represent the lower and upper bounds of most of the data, and the dots are outliers.



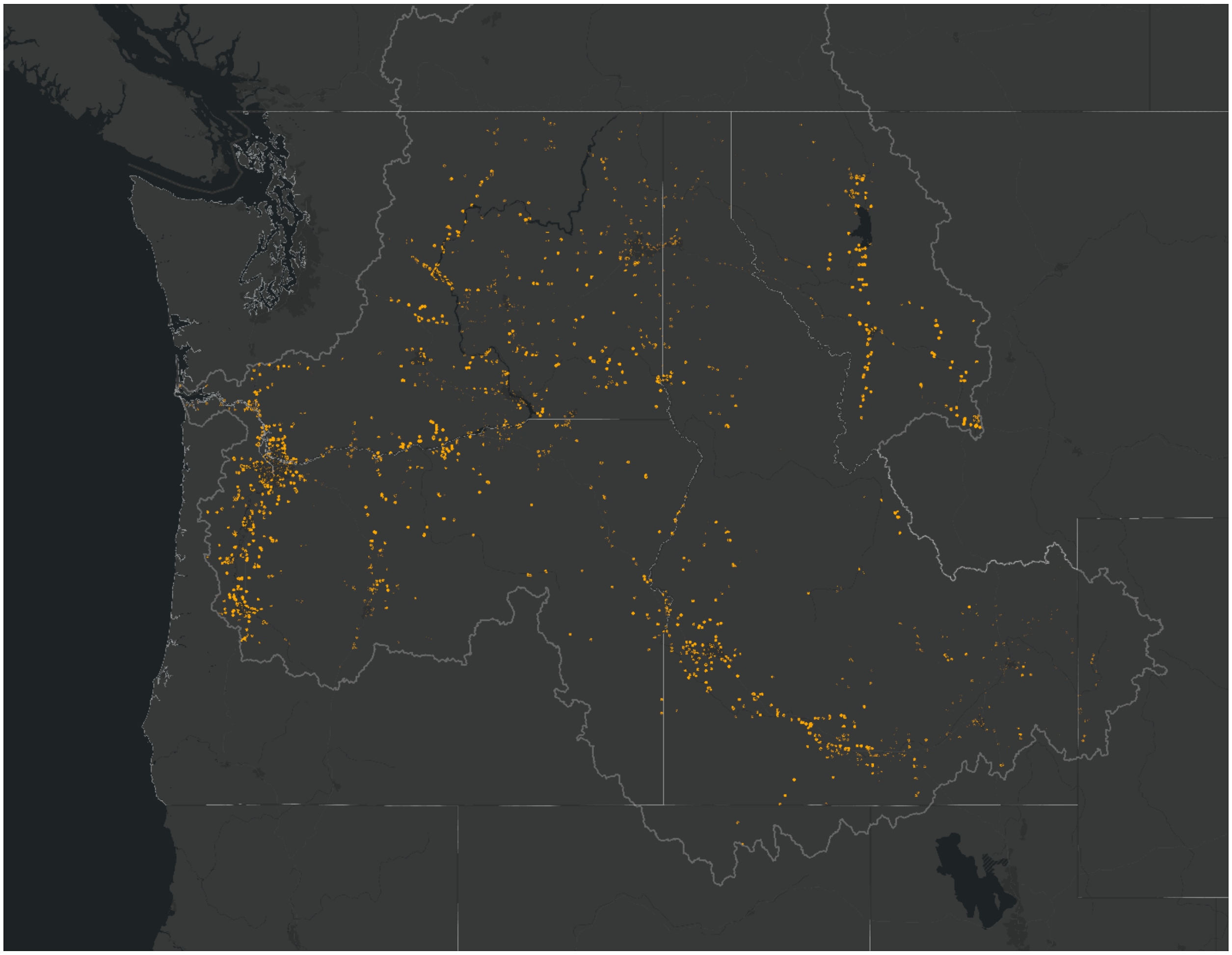
Appendix Figure 71. Boxplots showing the distribution of farmland productivity (PVR) as a function of low and high irrigation intensity farmland, different crop types that are amenable for agrivoltaics, and whether farmland is in eastern or western Washington. PVR is produced by American Farmland Trust and higher values indicate more productive and resilient farmland. Each box's center line is the median value, lower and upper ends of the boxplots are the 25th and 75th percentiles of the data, the two horizontal lines represent the lower and upper bounds of most of the data, and the dots are outliers.



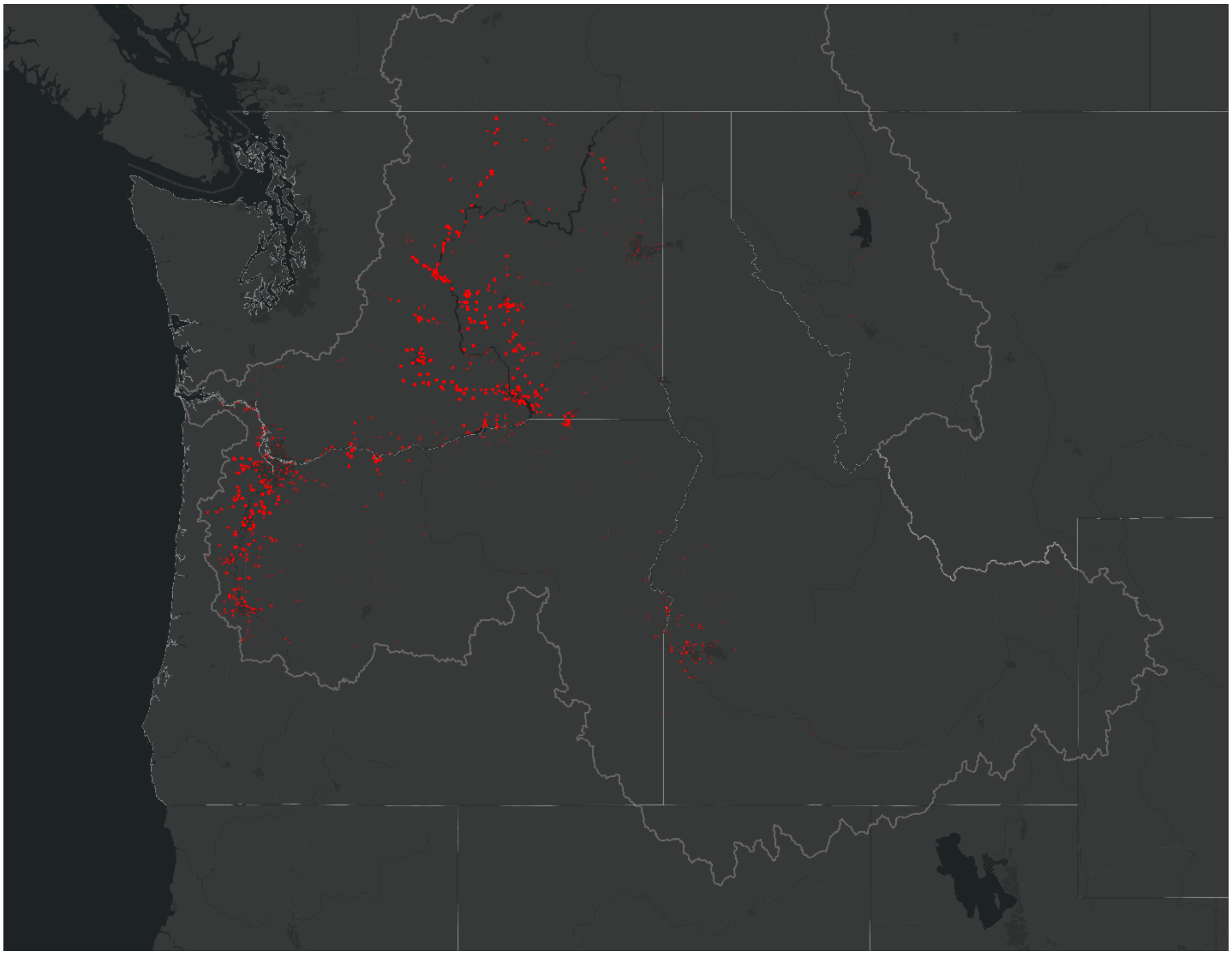
Appendix Figure 72. Boxplots showing the distribution of farmland productivity (PVR) as a function of different crop types that are amenable for agrivoltaics and whether farmland is in eastern or western Washington. PVR is produced by American Farmland Trust and higher values indicate more productive and resilient farmland. Each box's center line is the median value, lower and upper ends of the boxplots are the 25th and 75th percentiles of the data, the two horizontal lines represent the lower and upper bounds of most of the data, and the dots are outliers.



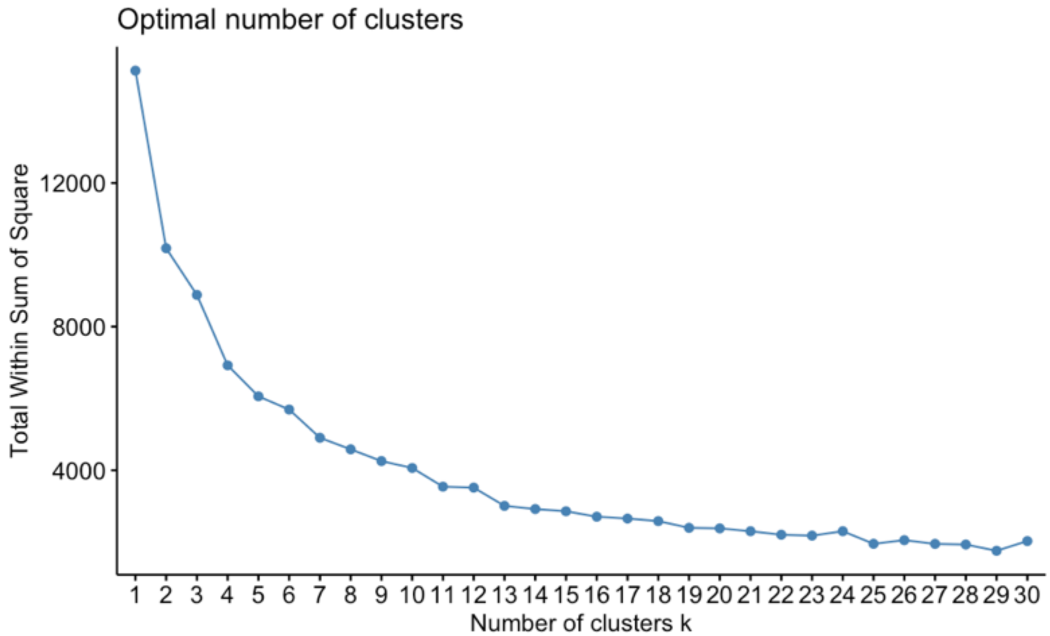
Appendix Figure 73. Farmland productivity (PVR) is inconsistently associated with solar energy potential (PVout). PVR analysis was developed by American Farmland Trust and higher values indicate more productive and resilient farmland. Lines represent best fit regression curves for each crop and side of Washington state.



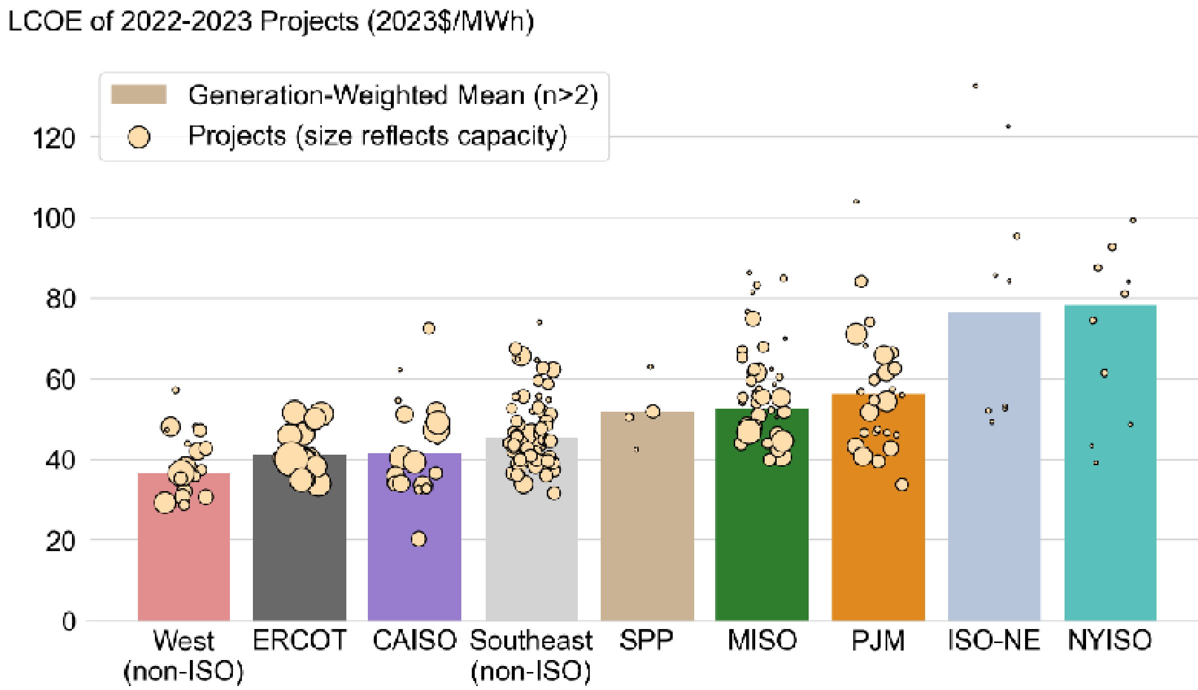
Appendix Figure 74. Potential agrivoltaic pastureland in the Columbia Basin that is within 1-mile of a substation based on USDA data.



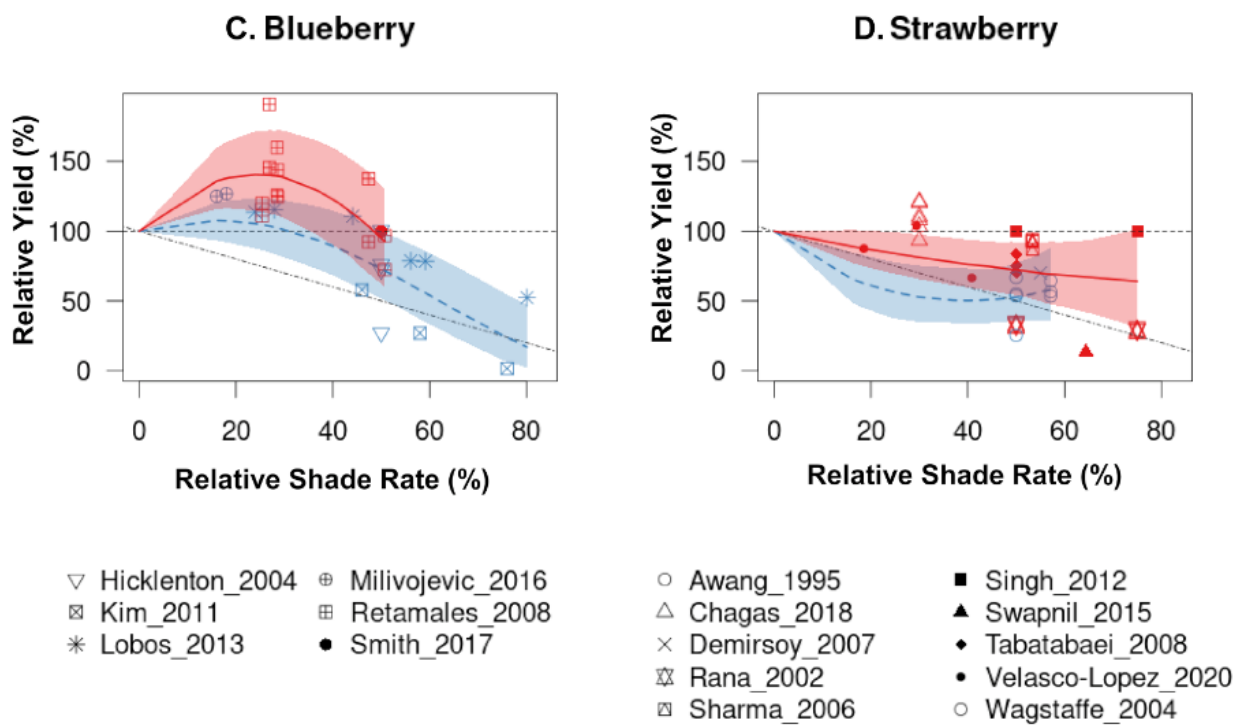
Appendix Figure 75. Potential orchard agrivoltaic land in the Columbia Basin that is within 1-mile of a substation based on USDA data.



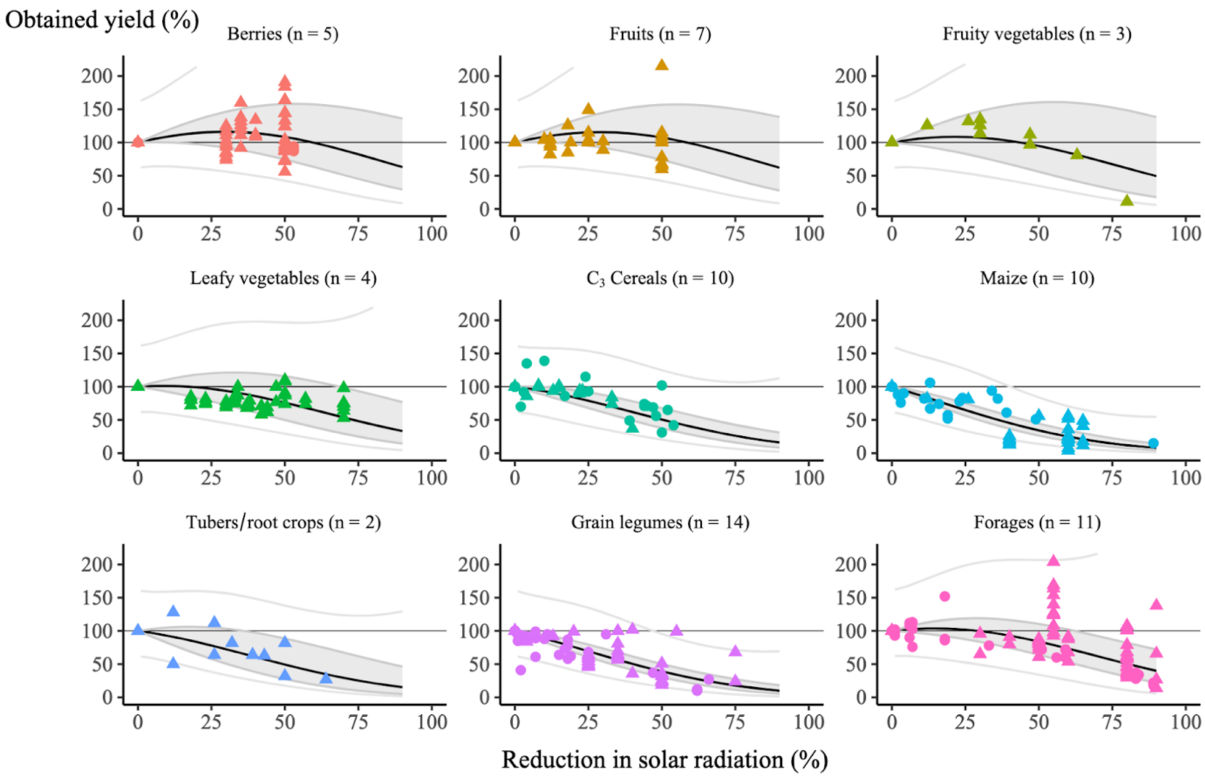
Appendix Figure 76. Elbow plot showing the within-cluster sum-of-square distances (sum of squared Euclidean distances from each point to its cluster centroid) as a measure of GridMET meteorological cluster cohesion or variance changes with the number of clusters. The "elbow" or inflection of the plot indicates the point of diminishing value of reducing the sum of square distances by increasing the number of clusters. Based on the inflection point, 10 clusters were chosen to represent the diversity of environmental conditions across central and eastern Washington's apple growing region.



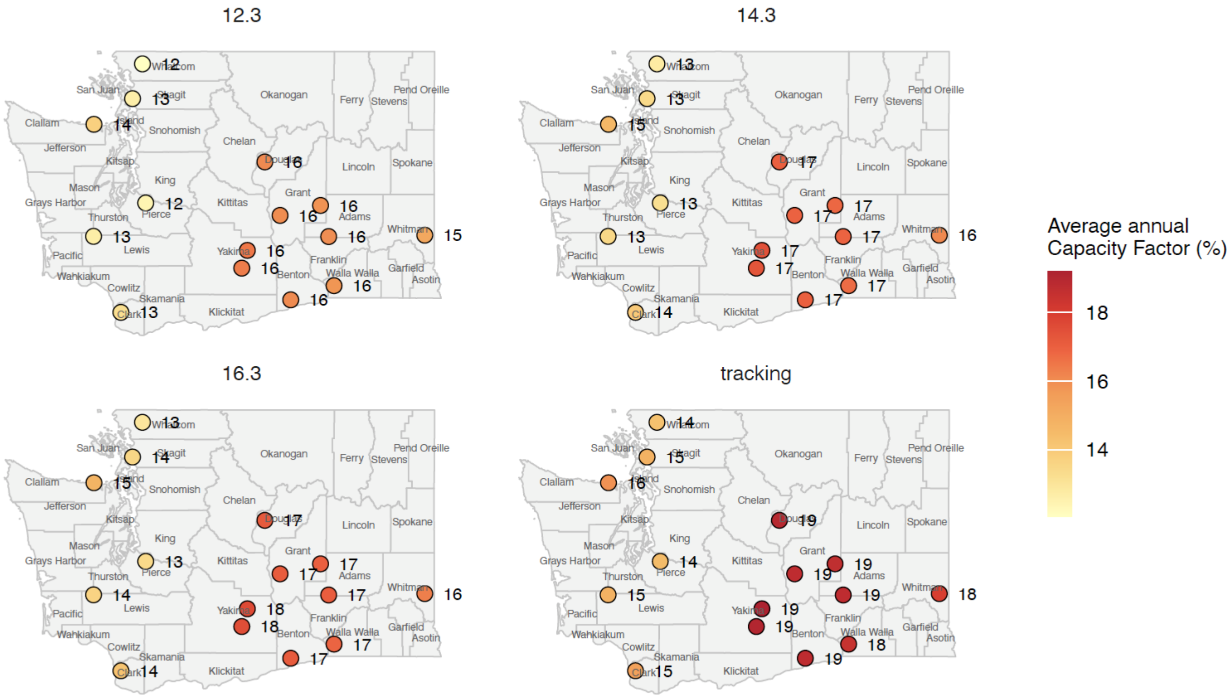
Appendix Figure 77. LCOE of solar projects developed in 2022-2023 for each major interconnection market in the US (Seel et al. 2024).



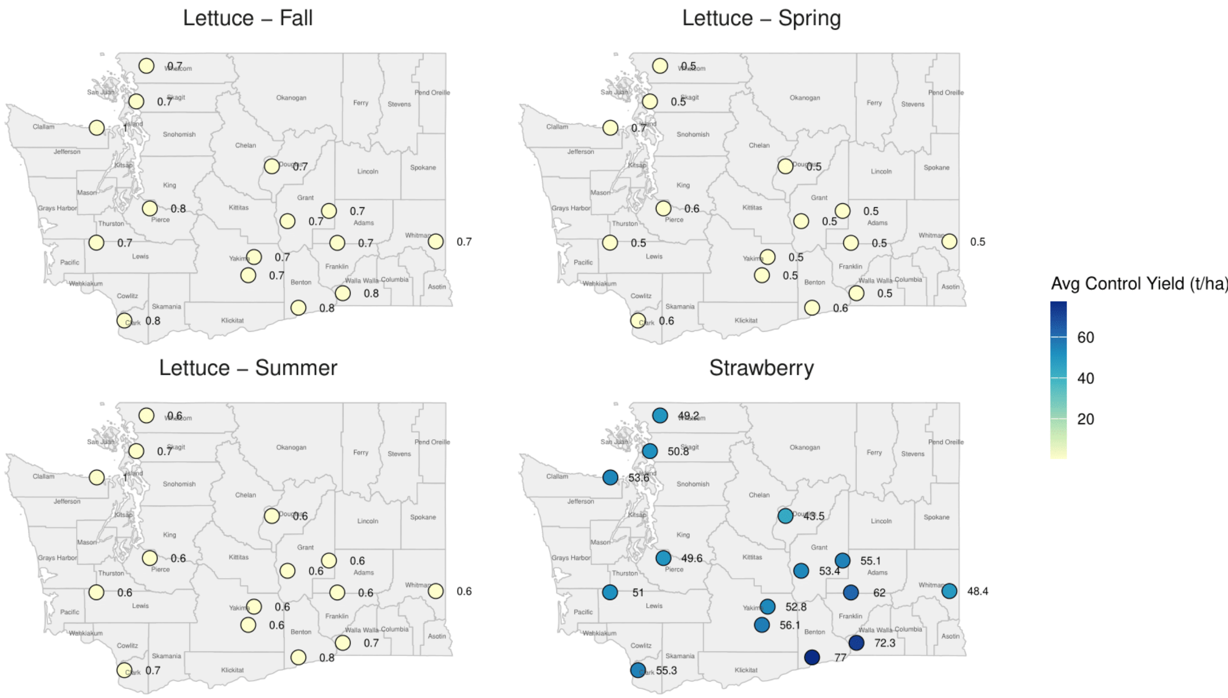
Appendix Figure 78. Response curves of relative yield to relative shade rate for (C) blueberry, and (D) strawberry at the low (blue, dashed line) and high (red, solid line) radiation intensity levels predicted by a mixed effects model in the meta-analysis of berry shade tolerance. The dotted lines indicate the direct proportional loss curve (diagonal, e.g. 10 % increase of relative shade rate results in 10 % yield decrease) and the 100 % relative yield (horizontal) as references. Reproduced from Figure 1 in (Hermelink et al. 2024) to use as a reference for simulated crop yields under PV panels in agrivoltaic array designs.



Appendix Figure 79. Meta-regressions (black line) of obtained yield as function of reduction in solar radiation. The dark grey shaded band and light grey lines depict the 95% confidence intervals and prediction intervals, respectively. Triangles (Δ) represent data from normal shading experiments and circles (•) are from intercropping experiments. Reproduced from (Laub et al. 2022) Figure 3 to serve as a reference for simulated crop yields under PV panels in agrivoltaic array designs.



Appendix Figure 80. Average annual capacity factors for fixed tilt arrays at three pitches (12.3, 14.3, 16.3 feet) and single-axis tracking arrays at representative berry and vegetable locations.



Appendix Figure 81. Site-specific cumulative yield of the unshaded (control) crop modeling case in tons/hectare. The strawberry yield corresponds to 90% water-saturated fruit mass, and the lettuce yield corresponds to 0% saturated biomass at harvest.

Appendix Figure 33: Farmer Survey Protocol

This survey is for farmers, ranchers, and agricultural landowners in Washington. American Farmland Trust (AFT) believes the interests, needs, and concerns of farmers and ranchers need to be heard and shared with decision-makers to more effectively build consensus around solar siting in Washington.

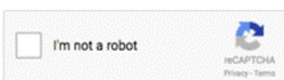
By completing this short survey, you will directly inform AFT's Smart Solar℠ strategy and influence policies to facilitate smart and thoughtful build-out of solar capacity in Washington while benefiting farmers and ranchers and minimizing displacement of agricultural land in Washington.

This 10 minute survey asks about your perspectives about solar on farmland in Washington. **Your responses will be kept anonymous**, so please share your honest feedback and opinions.

AFT will award $100 Visa gift cards to 25 randomly selected survey participants. Thank you in advance for completing this survey by March 30, 2025.

I. Introduction

*Before you complete the survey, please check the box to confirm that you are a farmer, rancher, or agricultural landowner in Washington



1) Which of the following best describes your role in the farm or ranch operation in Washington: (Select all that apply)

- I am the landowner
- I am the farmland owner-operator
- I am the spouse of the farmland owner-operator
- I am the farm-renter (tenant farmer)
- I am the farm/ranch manager
- I am an employee
- I am not involved with a farm or ranch in Washington (skip to end of survey/disqualification page)
- Other (please specify): _______________

3) **Which of the following do you primarily grow or raise?** (Select all that apply)

a. Apiary products and pollination services
b. Berries
c. Cattle
d. Field crops (grains, dry-legumes, oilseeds, fibers, hay, etc.)
e. Forest/Timber products
f. Grapes
g. Livestock and poultry **products** (milk, eggs, manure, wool, etc.)
h. Nursery crops

i. Nuts
j. Other livestock (goats, pigs, etc)
k. Pasture
l. Poultry
m. Seed crops
n. Sheep
o. Tree fruit
p. Vegetables/small fruits
q. Other (please describe): _________________

4) How many acres, on average, were a part of the farm or ranch over the past 3 years? (optional)

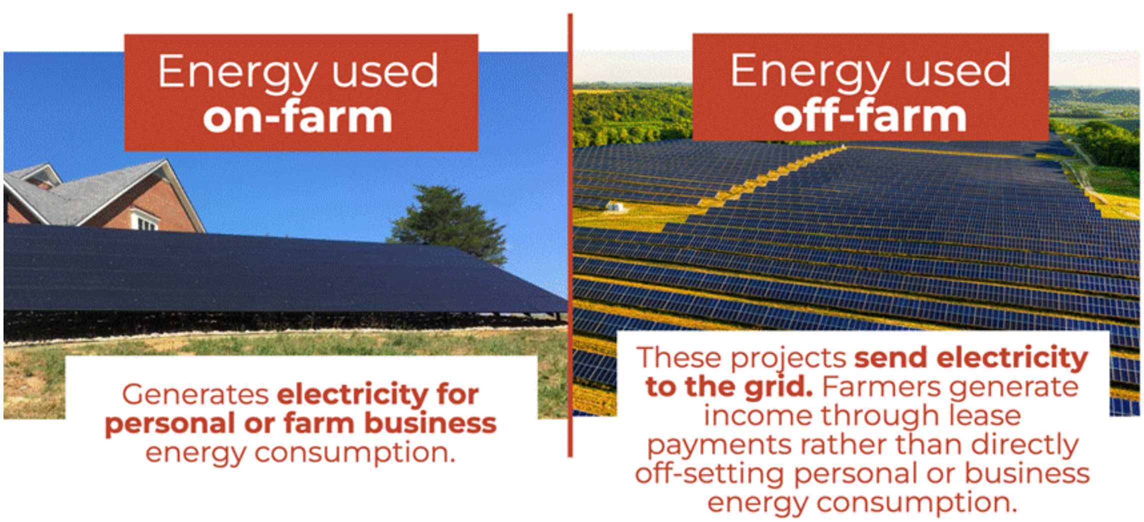
a. Less than 10 acres
b. 10-50 acres
c. 51-100 acres
d. 501-1,000 acres
e. 1,001-10,000 acres
f. Above 10,000 acres

4a) Which of the following best describes your agricultural land?

e) I own all of my land
e) I mostly own my land
e) It's about 50/50 (own rent)
e) I mostly rent my land
e) I rent all of my land

II. Attitudes about Solar & Agricultural Land

The following questions will ask about your opinions regarding **ground-mounted solar** development on agricultural land in Washington. These projects typically have a 30-35 year[1] lifespan. Please refer to following definitions:



American Farmland Trust
SAVING THE LAND THAT SUSTAINS US
WSU TRI-CITIES Institute for Northwest Energy Futures
The Nature Conservancy
UC SANTA BARBARA

5) In general, do you support building solar projects for off-farm/ranch energy consumption on agricultural land in Washington?

- Yes
- No
- It depends. Please describe: ____________________

6) How do you think solar development in Washington will impact the following?

	Negatively	No impact	Positively	I don't know
a.People who rent agricultural land (tenant farmers)				
b.Local community				
c.Land prices and land access				
d.Local agricultural services and supply chains				
e.Farm productivity				
f.Farmland preservation				
g.Soil quality				
h. The economic viability of agricultural operations				

7) I think solar developers should be allowed to build solar projects to generate electricity for off-farm/ranch consumption in Washington on:

	Never	Sometimes	Always	Not sure/ it depends
a.Most productive agricultural land (USDA Prime & Soils of Statewide Importance)				
b.Agricultural land with moderate limitations				
c.Marginal or least productive (non-prime) agricultural land				
d.Farm-owned forested land				
e.Land not suitable for pasture or cultivated use				
f.Active agricultural land, regardless of soil type				
g.Underutilized agricultural land, regardless of soil type				
h.Any agricultural land				
i.State and/or federally owned land				

7a. Please comment on your response to the previous question: (optional)

____

III. Attitudes about Solar on Your Land

8) Have you been contacted by a solar developer about leasing your land for solar?

- No
- Yes

- I don't know

Display only if answered "yes" to question above

8a) How many different solar developers have contacted you?

- 0 solar developers
- 1 solar developer
- 2-5 solar developers
- 6+ solar developers
- I don't know

Display only if answered "yes" to question above

8b) Did you receive a proposed per-acre lease rate for your agricultural land?

- Yes. The proposed lease rate (per acre) was ________
- No
- I don't know

9) Under what conditions would you be willing to host solar panels on your farmland to generate electricity for off-farm consumption? (Select all that apply)

- If the project provides me supplementary income
- If the project supports my ability to continue operating
- If I can continue farming under and around the solar panels
- If the solar infrastructure can be leveraged as shelter for livestock or shade for crops
- If the projects helps me pass the farm to the next generation
- If the project brings economic development opportunity to my community
- If I can have direct influence on the design and planning process
- I am not interested in leasing land for solar development under any condition
- Other (please describe): _______________

IV. Agrivoltaics

10) What is your familiarity with the concept of agrivoltaics?

e) Never heard of it
e) Have heard the term but do not understand the concept
e) Basic understanding
e) Firmly understand the concept
e) Deep understanding (direct experience, applied expertise)

(Add page break)

11) Based on the agrivoltaics definition and photos above, are you more or less likely to support solar projects on farmland in Washington?

c) I'm more supportive of solar on farmland if it is an agrivoltaic system
c) I'm less supportive of solar on farmland if it is an agrivoltaic system
c) No change

12) Are you interested in establishing an agrivoltaic system on your farm or ranch?

Not at all interested	Moderately interested	Very interested	N/A

Display only if answered "not at all interested" or "moderately interested" to question 12

12a) If you are NOT interested in agrivoltaics, what would make you more interested? (Select all that apply)

i) Financial incentives
i) More information around the decommissioning process
i) More information about how solar panels impact the soil
i) More information about how shade from solar panels affects crop/livestock yield
i) More information about how shade from solar panels affects crop/livestock quality
i) More information about the economics of agrivoltaics
i) More information about potential benefits of agrivoltaics
i) Seeing neighbors do it
i) Other ___________

Display only if answered "moderately interested" or "very interested" to question 12

12b) If you are interested in agrivoltaics, are any of the following barriers to you? (Select all that apply)

j) My land is not suitable for solar
j) Navigating my farming equipment around solar panels
j) Opposition from my community (family/friends/neighbors)
j) The way solar panels look/change the natural landscape
j) Uncertainty around how solar panels may impact the soil

j) Uncertainty about impacts of shade from the panels on crop/livestock yield
j) Uncertainty about impacts of shade from the panels on crop/livestock quality
j) Unknowns around the decommissioning process
j) I don't have enough information
j) Other ___________________

13) Would agrivoltaics be possible in your current production system?

d) Yes, please explain: ______________________
d) No, please explain: ______________________
d) I'm not sure
d) Other, please explain: ______________________

Display only if answered "no" or "other" to question above

13a) If no, what are the most significant barriers? (Select all that apply)

j) My land is not suitable for solar
j) Navigating my farming equipment around solar panels
j) Opposition from my community (family/friends/neighbors)
j) The way solar panels look/change the natural landscape
j) Uncertainty around how solar panels may impact the soil
j) Uncertainty about impacts of shade from the panels on crop/livestock yield
j) Uncertainty about impacts of shade from the panels on crop/livestock quality
j) Unknowns around the decommissioning process
j) I don't have enough information
j) Other ___________________

Display only if answered "no" or "other" to question above

13b) If agrivoltaics is not possible in your current operation, would you consider switching production systems/crop types to make agrivoltaics possible on some portion of your operation?

c) Yes
c) No
c) I'm not sure

Display only if answered "yes" or "I'm not sure" to question above

13c) If you switched production systems/crop types to make agrivoltaics possible, what would you switch to?

a. Grazing sheep under and around solar panels
b. Raising other livestock (e.g. cattle, poultry) under and around solar panels
c. Growing annual food crops (e.g. vegetables) under and around solar panels
d. Growing perennial food crops (e.g. berries, orchards) under and around solar panels
e. Other, please describe: _______________

Display only if answered "yes," "I'm not sure" or "other" to question #13.

14) Would any of the following activities be possible on your land?

	N/A	No	Maybe	Yes
a.Grazing sheep under and around solar panels				
b.Raising other livestock (e.g. cattle, poultry) under and around solar panels				

c. Growing annual food crops (e.g. vegetables) under and around solar panels				
d.Growing perennial food crops (e.g. berries, orchards) under and around solar panels				
e.Navigating tractors and farm equipment under and around solar panels				

15) Who would you trust to provide more information on agrivoltaics? (Select all that apply)

- Attorney
- Conservation districts
- Electric utility
- Extension services (WSU)
- Family member(s)
- Federal Agencies (e.g. USDA)
- Farm associations and assistance programs (e.g. Farm Bureau, etc.)
- Land trusts
- Neighbors / Fellow farmers
- No one
- Solar developers
- State agencies (e.g. WSDA, Commerce, etc.)
- Local officials (e.g. Planning Board, Town Board)
- I've done my own research
- Other (please describe): ______________

16) Would you like to share anything else about agrivoltaics or solar siting on agricultural land in Washington? _________________________________

V. Demographics

17) How long have you been farming?

- Under 10 years
- 11-20 years
- 21 years or more

18) How old are you?

- Under 35
- 35-44 years
- 45-54 years
- 55-64 years
- 65 years and over

19) Gender: How do you identify?

- Female
- Male
- Prefer not to say
- Prefer to self-describe: _________

20) Which categories describe you? (Select all that apply)

- Asian or Asian American
- Black or African American
- Hispanic, Latino or Spanish Origin
- Middle Eastern or North African
- Native American or Alaska Native
- Native Hawaiian or Other Pacific Islander
- White
- Other race, ethnicity, or origin (please specify) ______________________

21) Have you served on active duty in the U.S. Armed Forces, Reserves, or National Guard?

- Yes, on active duty now
- Yes, on active duty in the past but not now
- No

22) Does your farm have an identified successor?

a. Yes
b. No
c. I don't know
d. Other (please describe) __________

22a) Would you be interested in follow-up support from AFT with your farm/ranch succession plan?

a. Yes (please provide your contact information below)
b. No

23) Would you be willing to engage in follow up conversations on these topics in the future?

a. Yes (please provide contact information below)
b. No thank you

24) If you would like to enter the drawing for a $100 Visa gift card, please provide your name and email below (your responses will remain confidential)

- Name (first): _________________
- Name (last): _________________
- Email: ______________________

END OF SURVEY MESSAGE:

THANK YOU! American Farmland Trust (AFT) appreciates your participation and thoughtful responses. We will hold follow up conversations and listening sessions to further inform program and policy development to maintain and preserve farmland viability in Washington. Your input in these continued efforts is extremely valuable.

[1] https://emp.lbl.gov/news/new-study-finds-increase-expected