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LETTER

Drivers of agrivoltaic perception in California and North Carolina

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Abstract

The last decade has seen dramatic growth in solar power. In some regions, the most favorable land for solar panels is farmland, which is often flat and exposed to high levels of irradiance. At the same time, the agricultural sector is faced with growing challenges, notably changing water availability and increasingly frequent extreme weather events. The combination of these trends presents an opportunity for a synergistic relationship between the agriculture and solar sectors: agrivoltaic systems (AVS). In AVS, solar panels are placed above and between crops, such that the same land produces both food and energy. This system has beneficial microclimate impacts, such as reduced evapotranspiration. Yet, despite these benefits there has been limited uptake of AVS. One reason may be hesitation on the part of farmers, whose perceptions of AVS have been explored little. This analysis seeks to address part of this gap by exploring the relationship between farmer perceptions and interest in AVS. A Likert scale survey was designed and distributed to farmers across two large, agriculturally productive states, North Carolina and California. Responses from the 41 participants who fully completed the survey suggest that farmers who perceive AVS as diversifying their income or whose goals include reducing water use are the most interested in installing AVS. Respondents also identified financial viability as a major concern, agreeing that upfront cost is a major barrier to AVS, and markets as the most influential driver of crop decisions. These findings provide insights for policymakers interested in expanding AVS, particularly in response to environmental stressors, such as water scarcity and extreme weather events. They also suggest the aspects of AVS that may be most important to farmers, and most effective in encouraging AVS uptake. This information can support efforts to promote AVS, contributing to sustainable agriculture.

1. Introduction

A global focus on reducing greenhouse gas emissions and mitigating the effects of climate change has driven large scale investment in renewable energies. For solar power, this shift has led to an estimated 240 GW of capacity as of 2022, with 73.5 GW in the US alone [1]. But solar energy has a large land footprint compared to conventional thermal sources of generation [2], and requires high levels of irradiance. This has drawn solar developers to farmland, which typically has high sun exposure and low slope, reducing the work required to prepare land for panel installation [3]. However, concerns that solar may thereby displace farmland have fomented tensions surrounding land use in agricultural communities [4].

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A potential solution is agrivoltaic systems (AVS), which take advantage of the complementary nature of solar generation and agricultural production. In AVS, crops are planted beneath and between solar panels. The solar array is designed to allow for planting and harvesting, by changing the density of the panels and/or raising them to allow machinery through. Though the concept of agrivoltaics was first proposed in the 1980s [5], research and media interest in AVS has taken off in the last decade, with the number of studies on the topic increasing several-fold [6].

Benefits of AVS can increase the resilience of agriculture. For example, in dry areas like the US Southwest and West, AVS can reduce the water usage of crops and mitigate extreme heat by providing shelter for crops [7]. In fact, under water-stressed conditions, yields from rainfed crops may be superior in AVS than in single use farms [8]. More broadly, solar panels can protect crops from extreme weather [9]. This effect has been explored in apple [10] and pear [11] orchards, where the panels act to partially replace shading and hail protection structures, with the potential to shelter plants against sunburn and heavy rainfall. Dual solar and agricultural land use can also aid farmland repurposing efforts in places where water scarcity, deteriorated soils, or excess pollution are impacting the ability to farm; AVS provide a secondary revenue stream to offset reductions in planted hectares and reduce the need for irrigation. Thanks to these benefits and concerns over limited land availability, governments in Japan, France, Germany, and elsewhere have begun actively promoting AVS.

Despite the attention on AVS, much of the literature has been limited to pilot projects observing impacts on crops or theoretical modeling. This includes experiments utilizing lettuce, tomatoes, peppers, cucumbers, and rice in regions like Northwestern/Southwestern US [7, 12], France [12–16], Italy [8], Germany [17], and Japan [18], along with modeling focused on the financial elements of AVS [19, 20] and on improving the efficiency thereof [21]. Little research has explored the individual behaviors related to AVS: how do farmers perceive AVS and choose whether to install them? There is substantial literature on farmer behavior, perception, and adoption of different farming practices [22, 23] as well as on photovoltaic adoption in a non-agrivoltaic context, i.e., on a separate plot of land [24]. Broader literature on technology adoption, such as the diffusion of innovations theory [25], provides a framework for understanding the evolution of AVS, which can be used to suggest that AVS are still in the early phase of experimentation but are approaching wider implementation [26]. Yet, uptake of any new technology is typically limited when there are few adopters [27], creating an initial hurdle to AVS expansion and suggesting a need to understand how farmers perceive AVS in order to stimulate the systems' spread. The aforementioned research provides useful insights, including noting that profitability is a critical driver for technology adoption [28], but it is insufficient to guide incentives or policymaking related to AVS.

An exception consists of work conducted in Japan, interviewing and surveying stakeholders regarding concerns around, and merits of, AVS [29]. Participants in this study identified a variety of factors that would impact their decision to install AVS, many of which were related to new income, upfront cost, and impacts to agricultural practices and crops. Notable findings included a strong relationship between positive perception of economic impact and positive perception of AVS, with a plurality of respondents predicting net positive impacts from agrivoltaic installations. Other researchers [26] conducted in-depth, semi-structured interviews with 11 farmers across the United States (US) and identified major concerns surrounding AVS' implementation including long-term land productivity and planning, market uncertainty and observability of benefits, and compatibility with current practices.

This paper builds on these existing frameworks and results [26, 29], contributing to the literature regarding farmers' perceptions of AVS. The aim of this work is to identify perceptions and traits correlated with farmers' interest in AVS. We distributed Likert-scale surveys to farmers in two US states with high levels of solar penetration, substantial agricultural productivity, and potential for land repurposing, California and North Carolina. The survey was designed to elicit opinions related to AVS, exploring the topics of land productivity and financial concerns. This analysis may help policymakers considering the impacts of land use change in rural areas and ways to increase the compatibility of agriculture and solar power.

2. Methods

Likert-scale surveys circulated to fruit and vegetable growers between July of 2021 and July of 2022 form the basis for this analysis. The research was considered exempt from review by the relevant Institutional Review Boards. Participants were provided with an informed consent form (supplementary materials, SM). The anonymous survey was hosted on Qualtrics and data were downloaded as an Excel spreadsheet (see SM) and analyzed both in Excel and in RStudio version 2022.07.1 + 554 [31]. The following sections provide more detail on the survey design (section 2.1) and sampling strategy (section 2.2).

Table 1. Likert scale statements used in the survey, along with the strength of agreement and level of contestation for each statement. Colors separate the question blocks. Questions were presented in the below order, in individual 'blocks' (i.e. different online 'pages'), denoted by the alternating colors.

Statement	Strength of agreement (mean)	Level of contestation (standard deviation)
1. I would be interested in making my farm an agrivoltaic system	0.34	1.06
2. Upfront cost is the major factor in deciding whether I would install an agrivoltaic system	1.1	1.22
3. I am worried an agrivoltaic system would reduce my crop yield	−0.37	1.18
4. I think adding solar panels to my farmland would help make the farm more profitable	1.29	1.02
5. I would keep farming even if selling solar power provided me with enough income to live	1.29	1.01
6. I think that adding solar panels to my farmland would diversify my farming income, reducing my risk	0.76	0.89
7. I have a positive perception of solar power	1.2	1.01
8. My goal is to lower costs	0.98	0.85
9. I want my children/relatives to continue farming	0.93	1.01
10. My goal is to maximize my farm's gross sales	1.07	1.13
11. I care about reducing my farm's water footprint	1.24	0.73
12. Farming is just a job	−1.29	0.87
13. I plan on expanding my farm	0.41	1.16
14. I am willing to use some portion of my land to test new technology and techniques	0.95	0.71
15. I care how many farms there are in my area	0.88	1.27
16. I am not interested in changing my farming choices even if it is equally costly	0.71	0.87
17. I am not interested in changing my farming choices even if it saves me a little money	0.93	0.72
18. I am not interested in reducing my farm's water usage even if I can afford it	1.1	0.86
19. Weather and water availability are the biggest risk to my farm income	0.56	1.21
20. I cannot afford to make large capital investments in my farm	−0.41	1.07
21. I prefer slightly lower, fixed revenues instead of unpredictable, but potentially higher, revenues	0.24	0.94
22. Market prices make my farm revenues unpredictable	0.12	1.22
23. My biggest costs are fixed, or overhead	−0.03	1.07
24. I prefer planning my crops on a year-to-year basis instead of long term	−0.32	1.04

2.1. Survey

Existing survey work on solar power and agriculture, and focus groups conducted prior to our survey launch, informed development of this survey. In previous research and our focus groups, financial impacts emerged as the driving factor in deciding whether to install solar panels on farmland, both in terms of the possible benefits (i.e., new revenue stream) and the upfront costs [24, 26, 29]. Concerns with uncertain impacts to crop yield and land are another common theme [26]. This survey sought to explore these topics, adding questions directed towards revenue variability, overall farm costs, and financial risk, the latter of which is an important consideration in the context of technology adoption [32]. Finally, the survey also included consideration of factors more generally associated with changes in farming practices or behavior, including a willingness to test new technologies and different individual and farm goals. The survey originally designed by the authors was shortened and edited for clarity following the seven focus groups (see appendix A for more details). Questions related to perceptions of solar power generally and AVS appeared first, to maximize the number of responses relevant to AVS in cases where participants did not complete the full survey. Table 1 provides the 24 Likert scale questions used in the survey. Ordinal scales, including the Likert five-point scale used in this analysis, are often used for the assessment of attitudes, including for agriculture and solar energy. Responses were used to assess links between interest in AVS and (1) perception of solar power; (2) impact of weather variability and financial stability; (3) risk aversion; and (4) location, land ownership, and crop type.

A final section on demographics did not use the Likert scale and collected information on farmer characteristics, including age, education, ethnicity, gender, zip code, irrigation usage, revenues, and use of solar. Figure 1 was used to illustrate AVS, accompanied by the text in the caption, which defined AVS as including panels over and between crops and which emphasized that there is no singular AVS arrangement.



Figure 1. Sample illustration of AVS used in the survey. Reproduced with permissions from [33]. The following text was used to describe the system.

"Agrivoltaic systems have solar panels installed in fields over and between rows of crops. The panels are spaced to make sure that harvesting equipment and other farm machinery can still pass through them. Instead of being low to the ground, the solar panels can also be raised higher, to allow taller crops to grow underneath them. Agrivoltaic systems can be arranged in many different ways. Current demonstrations have arranged solar panels with grape vines, tree crops, and vegetable crops (especially lettuce, cucumbers, and tomatoes). Although the solar panel posts take up some land that was formerly planted, preliminary research suggests that solar panels can provide shade and reduce temperatures for crops. This can result in reduced evapotranspirative demand. The solar panels also benefit from reduced temperatures below."

The statement *'I would be interested in making my farm an agrivoltaic system'*, the first statement in the survey (table 1), was used as the outcome of interest for this analysis, while other statements were used to evaluate factors associated with (or influencing) a participant's interest in AVS. The hypotheses at the outset were that interest in AVS is associated with (1) expectation of increased profits; (2) perception that AVS could diversify farm income; (3) preference for income stability; and (4) prior use of on-farm solar.

Not all respondents included information on crops grown. Because the focus of the analysis is AVS with crops, responses indicating only animal husbandry operations were dropped ($n = 1$). Questions with a minimum response rate of 50% were included in the analysis.

2.2. Study area and sampling

The survey relied on a convenience sampling strategy based on available directories of fruit, nut, and vegetable growers. Though convenience sampling is a non-probability sampling technique that does not allow generalization across entire populations, it is time and cost-effective [34]. Focus group participants were also asked to circulate the survey to their own contacts (i.e., snowball sampling), though this strategy was not heavily pursued. No compensation was provided to participants. Inclusion criteria were being over the age of 18 and working on a farm with food crops. Because over 80% of agricultural workers in California are most comfortable conversing in Spanish [35], materials were also translated into Spanish.

2.2.1. California

California is the most productive agricultural state in the US by cash receipts, with an agricultural sector valued at $55.8 billion [36]. Its 69 000 farms grow a variety of crops, the most important of which are grapes, almonds, and strawberries [37]. The state is also the top solar power producer in the country, with 41 675 megawatts of installed capacity [38], a trend set to continue given the 2018 mandate for 100% renewable and zero-carbon electricity for all retail sales by 2045 [39].

In addition, land use in California is changing dramatically thanks to multi-year droughts worsened by climate change. Declining water availability has resulted in farmer adaptations including groundwater pumping, which has contributed to the systematic depletion of groundwater resources [40] and led to the passage of the Sustainable Groundwater Management Act [41]. As a result of the legislation, about 364 000 hectares [42] of cropland will likely have to be repurposed to maintain California's aquifers at sustainable levels. Other adaptations include idling land, although this solution comes at the detriment of growers'

livelihoods and billions of dollars of lost revenues [43]. There is thus growing interest in ways to repurpose land while maximizing public benefits [44], including by converting portions of farmland to solar arrays [44, 45]. These changes in the agricultural landscape, and the importance of the agriculture and solar power sectors, make AVS particularly relevant to California.

In California, the survey was distributed both directly, by targeting farms with publicly available email addresses in California's Central Valley, as well as through the California Farm Bureau, an advocacy organization with 30 000 members [46]. Email invitations were sent to county chapters and individual farmers.

2.2.2. North Carolina

North Carolina is home to over 46 000 farms producing $12.9 billion worth of agricultural goods [47]. It is the country's top producer of tobacco and sweet potatoes and third in cucumbers [48]. In part thanks to strong state-level incentives, North Carolina has a flourishing solar industry, ranking fourth in the US in terms of generation capacity (8459 megawatts) [38].

In North Carolina, many of the debates surrounding expansion of solar power relate to environmental impacts and displacement of agriculture [49–51]. In fact, over 80% of utility-scale solar arrays are situated on what is considered agricultural land [52]. Another relevant issue in North Carolina is water quality; approximately 58% of the state's waterbodies were considered impaired in 2020 [53]. Integrating solar panels on agricultural land surrounding impaired waterbodies may be a means to reduce agricultural runoff and improve water quality while maintaining farmers' and landowners' income [53].

In North Carolina, the survey was directly distributed to all members of 'Got To Be NC' [54], an initiative on behalf of the North Carolina Department of Agriculture & Consumer Services, who were listed as growers of fruits and vegetables. Growers with email addresses or websites were sent the survey link along with an invitation to participate. Growers/producers with only a phone number were called directly.

2.3. Statistical analyses

For the purposes of correlation analysis, results from Likert scale questions were re-coded from categorical variables to numerical values, where 'Disagree Strongly' corresponded to a score of −2, 'Agree Strongly' corresponded to a score of 2, and 'Neutral' corresponded to 0. For negatively worded statements, the numerical values were reversed. Converting Likert scale data is an imperfect measure of the relationships between variables as there is not necessarily an absolute, or equal, distance between different responses (e.g. Disagree Strongly and Disagree versus Agree Strongly and Agree), nor a true neutral [55]. Responses to individual questions can also fail to capture the nuance in sentiment towards the concept being analyzed. Some researchers address these challenges by creating composite, summated scales [56] but these do not necessarily preserve or capture the full intent of a set of responses [57]. To increase the insights from this analysis, we present the results for individual questions as well as for summated scores representing perceptions of solar power/AVS, cultural value of farming (farming as a lifestyle), willingness to change (interest in modifying farm practices), and risk aversion (preference for stable, but perhaps lower, revenues) (see appendix B, table A2). Cronbach's alpha [58] is used to evaluate the internal consistency of the statements within the summated scale. The measure calculates the correlation between responses to questions to evaluate whether they can be considered related to the same concept, with values that range from 0–1, where a score of 0.70 and above is considered acceptable. The results present the correlation between interest in AVS and responses to other statements and summated scores because the small sample size precludes other, causal statistical analysis.

Differences between subgroups were evaluated using Fisher's test and the Kruskal-Wallis test. Fisher's test was used to evaluate differences in responses by demographic group, and was chosen in lieu of Pearson's chi-square test because some scale categories included fewer than 5 responses [59]. The test yielded no significant differences between demographic groups. The Kruskal-Wallis test, a non-parametric test used to compare more than two groups, was applied to evaluate the individual effects of location, sex, age, land quality, income, and education on interest in AVS. Categories with fewer than 5 samples were aggregated (age groups 65-74 and 75+; high school and technical certificate groups). Finally, the Copeland method [60] was used to identify the overall ranking of actors influencing participants' decision making. The Copeland method uses the results of pairwise ranking by stakeholders. The number of times an alternative is preferred over another is summed, while the number of times it does not is subtracted. The top ranked alternative has the highest total score.

3. Results

Seventy-one individuals submitted survey responses, of which 58% ($n = 41$) fully completed the survey and met eligibility. Nearly half of the respondents (44%) expressed interest in AVS (agree, $n = 14$; agree strongly,

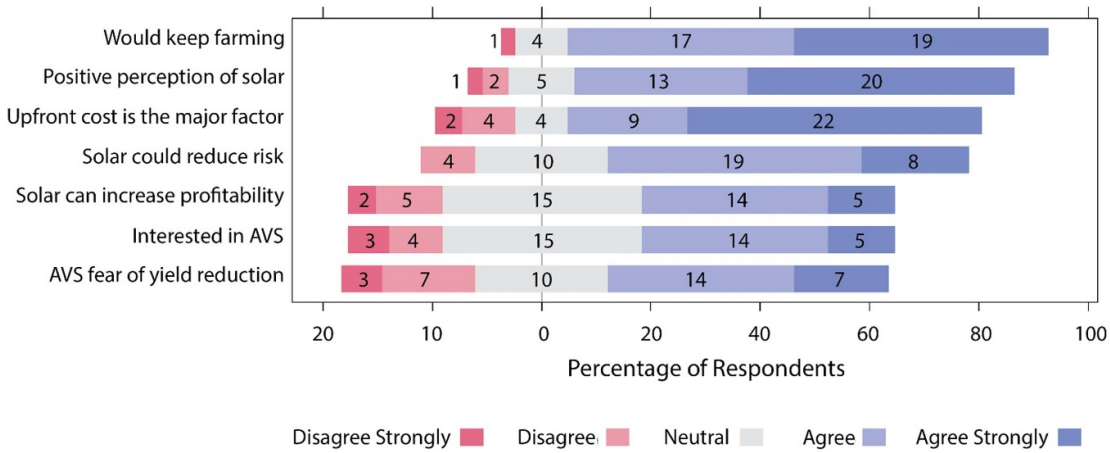


Figure 2. The distribution of responses to statements related to solar power and AVS. Numbers on bars indicate the count in each response category. Nearly all respondents agreed that they would continue farming even with sufficient income from solar, and that they had a positive perception of solar. Respondents were most split on whether they were interested in making their farm an agrivoltaic system and whether they were concerned that AVS would reduce their crop yields.

Table 2. Response to 'I would be interested in making my farm an agrivoltaic system' in landowners versus non-landowners. Percentages may not sum to 100 because of rounding.

Combined results	Agree strongly	Agree	Neutral	Disagree	Disagree strongly
Landowners	14%	31%	34%	14%	7%
Non-landowners	8%	42%	42%	0%	8%
Total	12%	34%	37%	10%	7%
California	**Agree strongly**	**Agree**	**Neutral**	**Disagree**	**Disagree strongly**
Landowners	8%	31%	38%	15%	8%
Non-landowners	0%	67%	33%	0%	0%
Total California	5%	42%	37%	11%	5%
North Carolina	**Agree strongly**	**Agree**	**Neutral**	**Disagree**	**Disagree strongly**
Landowners	19%	31%	31%	13%	6%
Non-landowners	17%	17%	50%	0%	17%
Total North Carolina	18%	27%	36%	9%	9%

$n = 5$), with a plurality ($n = 15$) expressing neutral sentiment (figure 2). Only 17% of participants reported that they were not interested in making their farm an agrivoltaic system. Ten respondents (24%) generated solar electricity on their farm, with one generating both solar and wind, of which three were interested in making their farm an agrivoltaic system, one expressed disagreement, and the remainder expressed neutral sentiment. For most respondents (76%), upfront cost was the major factor in deciding whether to install an agrivoltaic system. About half of respondents (51%) were concerned that an agrivoltaic system would reduce their crop yield, while the remainder neither agreed nor disagreed that they were concerned. Most participants had positive perceptions of solar power.

Landowners were more likely to express that they were not interested in AVS than non-landowners (21% versus 8%), and they were less likely to express neutral sentiment (34% versus 42%) (see table 2), though these results were not statistically significant. Trends differed between California and North Carolina respondents. In California, non-landowners expressed interest in AVS more often than landowners (67% versus 39%), whereas in North Carolina landowners were interested more often (50%) than non-landowners (34%).

Survey respondents were split nearly evenly between North Carolina and California as well as between male and female (51% and 41% respectively, 8% did not respond), with no marked differences in interest in AVS by category (see appendix B, figures A1 and A2). However, within the states, respondents were concentrated in California's Central Valley and North Carolina's Piedmont region (appendix B, figure A3). A wide variety of ages were represented, with 41% of farmers less than 45 years old. Most participants identify as not Hispanic or Latino and hold at least a bachelor's degree (table 3).

Survey participants were asked to inform who influenced their decisions by ranking the following options: Family and friends; Markets; Banks; Colleagues (other farmers); Academics; Certified crop advisors;

Table 3. Demographics of respondents ($n = 41$) who completed the survey and met all eligibility criteria. Where the count sums to less than 41, respondents left the field blank.

Question	Response	Count
Age	25–34	8
	35–44	9
	45–54	7
	55–64	8
	65+	6
	75+	2
Sex	Male	21
	Female	17
Ethnicity	Not Hispanic or Latino	35
	Both 'Hispanic or Latino' and 'White'	1
	Prefer not to respond	5
Education	High school	1
	Technical college or trade certification	2
	Some college	5
	Bachelor's degree	20
	Graduate degree	12
State	North Carolina	22
	California	19

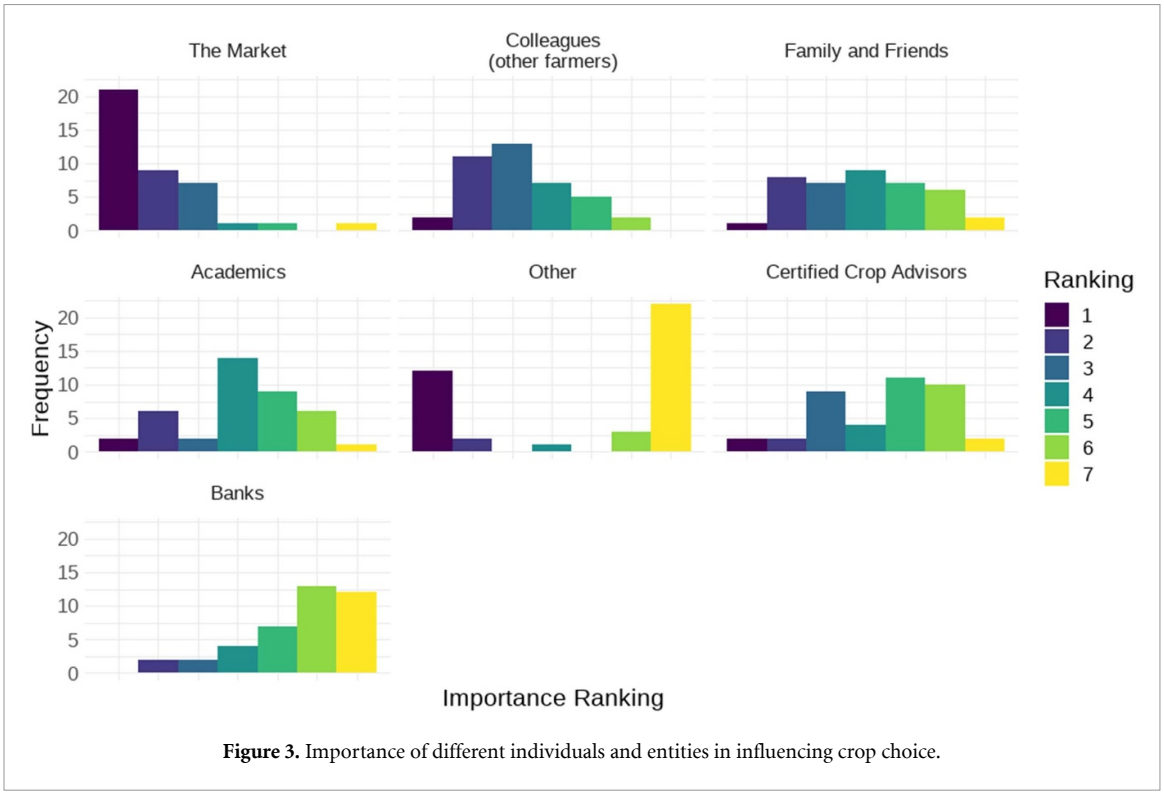


Figure 3. Importance of different individuals and entities in influencing crop choice.

or Other. Markets were ranked as the most important factor using the Copeland method, with other farmers ranked as second most important (figure 3). Banks, on the other hand, were ranked as the least important. Among the respondents that chose 'Other' as their primary driving factor, multiple specified beneficial practices, e.g., regenerative/sustainable agriculture and potential for value-added goods to reduce food waste. Most respondents choosing 'Other', however, identified personal experience or preferences as drivers for their decision making (see appendix B, table A3), while almost everyone who gave the lowest priority to 'Other' left the text blank.

As in similar survey work using Likert scale data, mean scores were used to test the strength of agreement with a sentiment, and the standard deviation was used to assess how contested a sentiment is [22]. The strongest agreement (highest mean value) was with the statement *'I would keep farming even if selling solar*

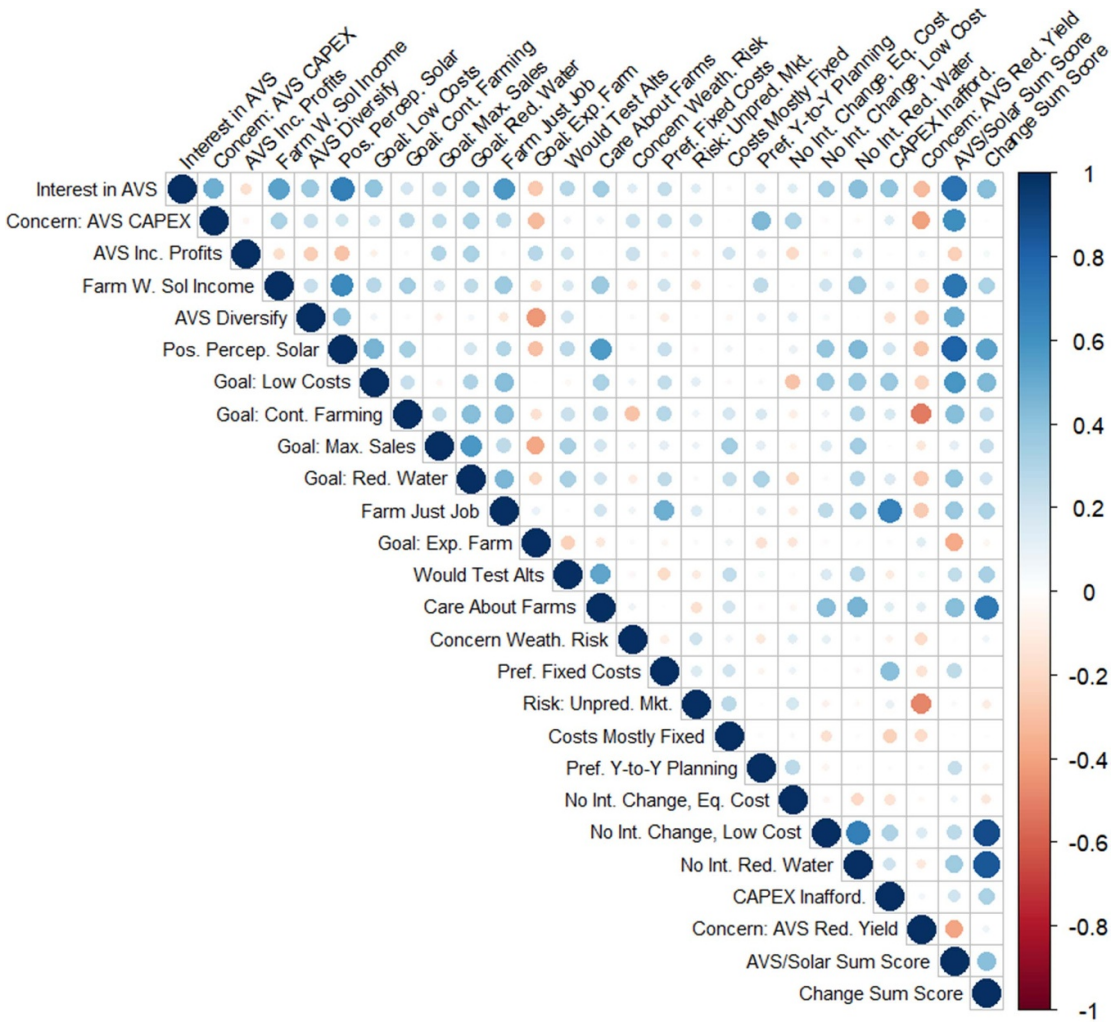


Figure 4. Correlations between statements used in the survey. Correlations are based on numerical values for agreement, which are scored from −2 (Disagree Strongly) to +2 (Agree Strongly), aside from the summated scores ('Change Sum Score', 'AVS/Solar Sum Score'). The latter scores are the total sum of the relevant questions, i.e., −6–6 (3 questions) and −12–12 (6 questions), respectively. See supplementary materials (Survey Results) or Appendix Table A4 for a key with the full statements used.

power provided me with enough income to live', while the strongest disagreement (lowest mean) was with the statement '*Farming is just a job.*' The largest standard deviation (highest level of contestation) was for the statement '*I care how many farms there are in my area*', while the smallest (lowest contestation) was '*I am not interested in changing my farming choices even if it saves me a little money*'. Other statements with high levels of agreement referred to positive perceptions of solar and the profitability thereof. Statements referring to costs and risks had notable levels of contestation, specifically those identifying market prices or weather volatility as the primary risks to farm income, and the importance of upfront cost in deciding whether to install AVS. It is also worth noting that some questions with high levels of agreement also had high levels of contestation, or more variability (measured as the standard deviation), in responses between participants. For example, on average participants agreed that upfront cost is a major factor in deciding whether to install AVS (mean = 1.1), but the standard deviation in responses was 1.22. Other questions had strong agreement (or disagreement) with little contestation, e.g., caring about reducing one's water footprint (mean = 1.24, standard deviation = 0.73). Table 1 provides the mean scores and standard deviations for each Likert Scale question (also see appendix B, figure A4).

Summated scores were calculated for the Solar/AVS block as well as for the cultural value of farming, willingness to change, and risk aversion. Only 14 of the 24 questions were used to create the summated scores, while the remainder were analyzed independently. Only the Solar/AVS and willingness to change blocks had sufficient internal consistency to represent a single sentiment, with $\alpha = 0.69$ and 0.78 (Cronbach's alpha). Results are thus only presented for these two blocks, in addition to results in relation to individual statements. The Solar/AVS block, excluding the statement on interest in AVS, intuitively displayed a strong correlation with interest in AVS; out of a range of −1 to +1, the block had a correlation (p) of 0.74 (see

figure 4 and appendix B, figure A5). On the other hand, the willingness to change composite score had a lower correlation, $p = 0.42$. Other statements positively correlated with interest in AVS included agreement that upfront cost would be the major factor in deciding to install an agrivoltaic system; perception that the agrivoltaic system would diversify on-farm income; and a goal of reducing water usage. The agreement that upfront cost is a major factor for deciding whether to install an agrivoltaic system corresponds directly to many of the concerns raised during the focus groups (see appendix A). The perception that an agrivoltaic system would diversify on-farm income provides further evidence that financial cost-benefit analysis is a key factor in installing AVS. A desire to reduce water usage further points to logistical considerations—AVS have been shown to reduce evapotranspirative demand (as described in figure 1) and farmers interested in reducing water usage would logically be interested in this capability. Those that stated they could not afford large capital investments in their farm were also less likely to express interest in AVS—an intuitive relationship considering the cost of adding solar panels to farmland.

4. Discussion

Initiatives to expand renewable energy capacity, particularly solar, have exacerbated tensions between agricultural land users and energy developers [4]. In areas with limited available land, or where agricultural land is particularly well suited for solar energy generation, tensions may be reduced by combining agricultural production with solar energy generation in AVS. Adding solar panels to existing farms can support environmental stewardship and make farms more financially robust, thanks to AVS' impact on the microclimate [7, 61] and revenues [19, 20]. This can be particularly beneficial in regions where water scarcity forces farmers to temporarily idle or permanently repurpose land. Other changes, such as moving towards regenerative agricultural practices, have synergies with AVS, as adding solar panels can broaden the range of crops that can be feasibly grown by providing shade and shelter to sensitive crops. This can create new economic opportunities for agricultural communities while mitigating potential harmful effects of extreme weather and water scarcity.

Despite these benefits, AVS have not proliferated widely, and this survey provides initial consideration for why that may be. Results are in line with existing qualitative research, especially in that monetary incentives are the strongest driver for adding solar power to farms and farming communities [24, 26], a trend evinced by the number of respondents that both agree that adding solar to their farm could increase profitability and that they are interested in AVS. On the other hand, our discussions in the focus groups and agreement that upfront costs are the major factor in evaluating AVS suggest that adding solar to a farm may be financially infeasible or reduce profits in some cases.

It is also possible that concerns around AVS disrupting agricultural lifestyles are impeding the spread of AVS; as is documented in the literature, farming is often a component of farmers' identities [62, 63], and not 'just a job'. Respondents in our survey indicated strong ties to farming and a desire for their families to continue farming. This desire suggests that AVS could become a favorable alternative to solar because they avoid displacing agricultural production. In-depth, semi-structured interviews conducted with a small group of farmers and solar developers [30] found similar dynamics, namely that AVS could be used to support agriculture and surrounding communities. This information may help guide a shift towards prioritizing dual use solar projects, which may thus gain more buy-in from farming communities than single use solar. However, it also suggests that AVS promotion will be a delicate balance between framing solar as a secondary revenue stream and managing fears that solar will fully replace agriculture because of its profitability.

A desire to continue farming could also further motivate AVS, in terms of the systems' impact on water usage. This survey was the first to focus on water usage as a possible motivating factor, and indeed identified a strong, positive correlation between caring about reducing a farm's water footprint and interest in AVS. In parts of California like the San Joaquin Valley, where declining water availability is leading to need to idle land, systems and technologies that can reduce water usage can support farming even during irrigation restrictions. This finding opens the door to future research on how AVS can be designed to maximize water reduction, and with which crops. This survey was also the first to focus on perceptions of financial risk, and their relationship to AVS. Though prior modelling and survey work has identified secondary revenue as a clear benefit of AVS [19, 20, 26, 29, 64, 65], none have evaluated whether farmers associate AVS with risk reduction, nor whether risk aversion is correlated with interest in AVS. This work adds nuance to the literature by correlating a perception that AVS reduce financial risk with interest in them.

These factors, and the others identified in the survey, suggest several policy options for supporting AVS. First is improved outreach, extension, and communication. When considering installing an AVS, farmers in our focus groups had questions around yield, costs, and pilot programs. In the survey, most farmers identified cost as the largest factor in deciding to install AVS. Farmers were, however, less concerned about yield reductions than we expected, though responses varied substantially. Providing data to farmers on the costs of a crop-specific AVS design could alleviate a primary concern for farmers, as could crop- and geography-specific yield impacts. This points to the need for community-based co-development of pilot

projects and priorities, tailoring experiments and data collection to local concerns (e.g., water usage, soil health). Finally, 'other farmers' were ranked as the second largest influence on deciding how to manage one's farm, and so targeting farmers most interested in AVS to convert their farms may create a positive ripple effect across farming communities. These efforts could begin with focusing on the benefits to water usage, as respondents interested in AVS were also interested in reducing their water use.

Policymakers can support small and medium-sized farmers who are exposed to more financial and climate risk than large farms [66]. Small farms often have larger levels of crop diversity [67] and may be able to more easily pivot to new farming practices. Economic incentives, including subsidies or grants to defray AVS costs, or feed-in tariffs and power purchase agreements to guarantee revenues from power generation can encourage AVS uptake [24, 26, 29] and offset the high capital costs of AVS. These incentives may be offered in tandem with those promoting other agricultural practices such as decreased or modified pesticide use and better soil health practices (e.g., planting cover crops).

Together, these changes can have significant impacts for surrounding communities and contribute to environmental justice goals [44]. For example, in regions like California, where unsustainable water use for agriculture is driving a need for cropland repurposing, AVS may contribute to reducing water consumption. This can help support rural communities as they transition to an economy less dependent on agriculture, protecting farm workers and small and medium farmers. It can also reduce groundwater drawdown, potentially preserving access to drinking water in domestic and community wells [68, 69].

The insights generated in this study are a step towards understanding why farmers may or may not install AVS. Importantly, this survey stands in contrast to some coverage of AVS and ongoing policy efforts to inhibit them. We find positive, or at least neutral, perceptions of AVS among the majority of farmers that participated in the focus groups and/or survey, regardless of whether they have solar panels installed themselves, findings in line with prior research [26]. While the number of responses is a small fraction of the large number of farms in North Carolina and California, future qualitative research can expand on these findings, focusing on traits that have a strong positive or negative correlation with interest in AVS. For example, given the importance placed on upfront cost as a barrier to AVS, choice experiments or in-depth semi-structured interviews may help identify the maximum costs growers are willing to pay to install AVS, or the size of a subsidy needed to make AVS affordable. Future work can build on this survey by increasing the number of farmers, operators, and workers interviewed and surveyed. As the number of AVS expand, researchers can also take into account the impact of social learning and of 'community champions', evaluating whether AVS uptake accelerates after one farm converts to dual use within a community per existing theories of technology adoption.

5. Conclusions

Agrivoltaic systems can help to achieve renewable energy targets while simultaneously safeguarding agricultural land. Solar panels in AVS offer shade and protection for crops, mitigating the impact of extreme weather and decreasing water use. In places like California, such decreases could lead to reduced groundwater pumping and benefit the disadvantaged communities most impacted by increasing water scarcity. Finally, the revenues from power generation can improve the financial stability of farms.

However, agrivolataic system adoption depends on the willingness of farmers to integrate solar power systems into their operations. Understanding what priorities and concerns are linked to farmers' perceptions of AVS is essential to policymakers and solar power developers seeking to expand use of AVS. This analysis uses a survey to explore the links between farmer characteristics and interest in AVS. Designing systems that accommodate the insights of farmers and surrounding rural communities can preserve agricultural land, make agriculture more sustainable, and promote renewable energy.

Data availability statement

All data that support the findings of this study are included within the article and in the supplementary information files.

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CRediT statement

R I C: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Supervision, Writing—Original Draft, Writing—Review & Editing. A S F-B: Formal Analysis, Writing—Original Draft, Writing—Review & Editing. G W C: Funding Acquisition, Supervision, Writing—Review & Editing. M A N : Funding Acquisition, Investigation, Methodology, Writing—Review & Editing. M R: Investigation, Methodology, Writing—Review & Editing. M A-N : Conceptualization, Investigation, Methodology, Writing—Review & Editing, Supervision.

Conflict of interest

The authors declare that they have no conflict of interest.

Appendix A. Description of focus groups

The survey was designed by the authors but discussed with 22 individuals in small focus groups. The groups tested the survey but were not the core of this work and, as such, were not recorded. The one-hour focus groups were conducted virtually given the ongoing COVID-19 pandemic. Participants in the focus groups were selected so as to capture a range of responses representative of major crop types in California and North Carolina, and included a mixture of trade organization representatives, farmers, and extension specialists (see table A1). Focus groups were ended once responses to the questions consistently converged, and representatives of major crop groups were included.

Table A1. Focus groups conducted between March and July 2021. Groups were designed based on shared crop interests and/or geographic proximity to facilitate an understanding of the different concerns facing growers of different crops.

Farm location	Topic	Participants
CA	Processing tomatoes and annual vegetables	3
CA	Nut systems	3
NC	Vegetables	5
NC	Mixed	4
NC	Berries, tobacco, orchard	4
NC	Cotton	1
NC	Peanuts/cotton	2

In North Carolina, extension specialists working with specific crop types at the North Carolina State University were invited to participate. Similarly, trade organizations listed on the North Carolina Department of Agriculture & Consumer Services website [70] were contacted either by direct email (if listed) or by webpage contact form. Some participants also referred additional individuals. In California, cooperative extension advisers that worked with specific crops and scientific or outreach representatives from trade organizations were invited to participate via email. Though focus groups were intended to have between 3 and 6 participants, unexpected scheduling changes created focus groups as small as 1 participant.

Participants were sent the consent form and copy of the survey though they were not required to complete it prior to participation. One participant, who owns a small farm, had already installed solar panels on site, but otherwise no participants reported direct experience with on-site solar generation. Most participants were unfamiliar with AVS prior to the focus group and survey. A total of 22 individuals attended focus groups, with 6 in California and 16 in North Carolina. A two-person, post survey group was conducted in North Carolina in February 2022, at the end of survey collection with the purpose of exploring themes that had emerged in responses.

Focus groups involved a semi-structured format in which each section of the survey was reviewed and discussed, and a short video demonstration of AVS was accompanied by a verbal description (link: www.youtube.com/watch?v=BlXPf-e1a0U&t=1s). The first 10 minutes of the session were reserved for participants to take the survey if they had not already. Participants were encouraged to express their opinions on specific questions or AVS more broadly, and whether their understanding of dual use solar changed during the course of the discussion. The final question in the focus group identified three land use scenarios and associated crop yields and income: agriculture only, an agrivoltaic system, and a single use solar array. However, given feedback from the groups, these scenarios were not included in the final survey. The survey was also shortened based on focus group feedback.

Focus groups brought to light three major themes, in line with previous research on AVS [26, 29]: the financial impediments to AVS; the logistical challenges of implementation; and the need for side-by-side

comparisons of crop impacts, financial outcomes, and water usage in AVS and single use farms. Financial considerations were a major theme. Focus group participants noted that only the largest farms would likely be able to finance AVS, and that the addition of solar panels may impact a farm's taxation status, raising farm costs substantially. Participants viewed the large capital expenditures as the largest roadblock, especially given the risks involved, but commented that demonstrated monetary returns would make AVS an intuitive choice.

Several logistical challenges emerged. Most important was the ability to install panels with sufficient clearance to let large machinery (e.g. pesticide sprayers) pass below and between panels for crops with very mechanized planting and harvesting processes. Participants noted, for example, that in some cases multiple machines may normally operate simultaneously. In these cases, a solar installation would likely interfere with farm operations. It may also impede normal crop rotations between seasons or years. A second logistical challenge related to land ownership, because many farmers lease land as opposed to owning it directly. Without full ownership, farmers may be unable or unwilling to make decisions with regards to long-term land use.

A final consideration was coordination with the power utility. Participants voiced concerns around panel maintenance and the presence of utility workers in fields also noting that solar developers may also lack the incentive to build AVS versus single use solar arrays. This might be especially important when a farm does not offer clear advantages, such as existing transmission infrastructure, compared to unused land. Finally, in terms of individual impacts, participants were quick to note that a decision to install AVS would be highly dependent on the crops grown and location. Participants requested information on how shading would impact the specific crops they grew, noting that most crops had yields correlated with sun exposure. The desire for site-specific and more detailed information is consistent with farmers' concerns with new technologies in general [25, 27].

Appendix B. Additional figures and tables

In an attempt to capture participant sentiment with higher levels of reliability, we summed the scores from questions into four blocks: perceptions of solar power/AVS, cultural value of farming (family as a lifestyle and livelihood), willingness to change (interest in modifying farm practices), and risk aversion (preference for stable, but perhaps lower revenues) (table A2). Statements were evaluated on an individual basis, as well as within the summated scores.

Table A2. Questions associated with the four summated scales: solar power/AVS, cultural value of farming, willingness to change, and risk aversion. Of the 24 questions in the full survey, 14 were used to build summated scores.

Summated score block	Question
Solar power/AVS	Upfront cost is the major factor in deciding whether I would install an agrivoltaic system
	I think adding solar panels to my farmland would help make the farm more profitable
	I would keep farming even if selling solar power provided me with enough income to live
	I think that adding solar panels to my farmland would diversify my farming income, reducing my risk
	I have a positive perception of solar power
Cultural value of farming	I care how many farms there are in my area
	I want my children/relatives to continue farming
	Farming is just a job
	I would keep farming even if selling solar power provided me with enough income to live
Willingness to change	I am willing to use some portion of my land to test new technology and techniques
	I am not interested in changing my farming choices even if it is equally costly
	I am not interested in changing my farming choices even if it saves me a little money
Risk aversion	I prefer slightly lower, fixed revenues instead of unpredictable, but potentially higher, revenues
	I prefer planning my crops on a year-to-year basis instead of long term

Respondents were fairly evenly distributed between California and North Carolina, and by sex, as was their interest in AVS and in single use solar (appendix B, figures A1 and A2).

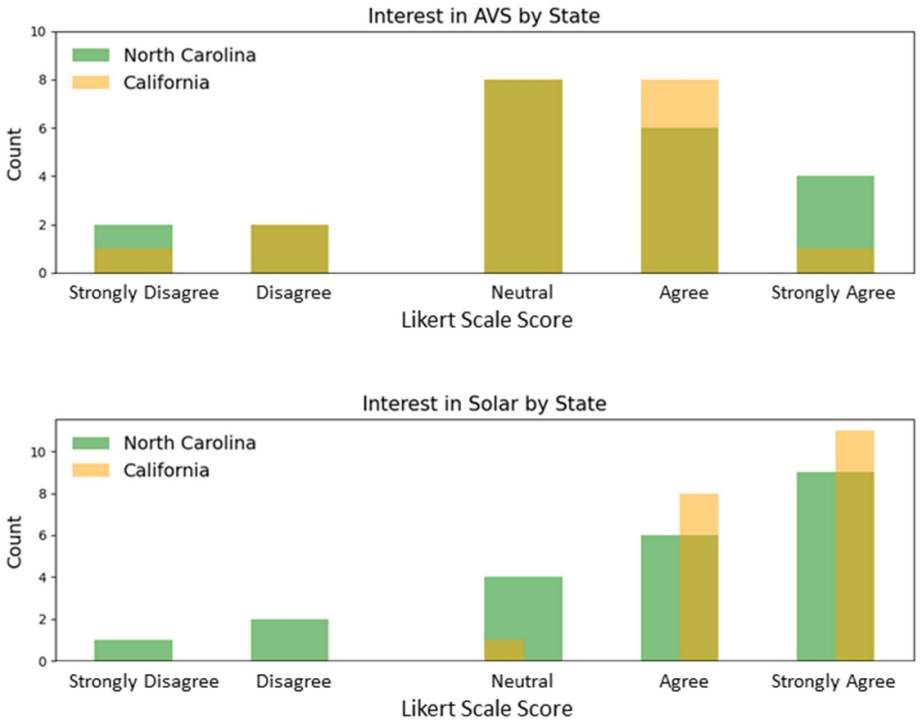


Figure A1. Interest in AVS (top) and solar broadly (bottom) by state.

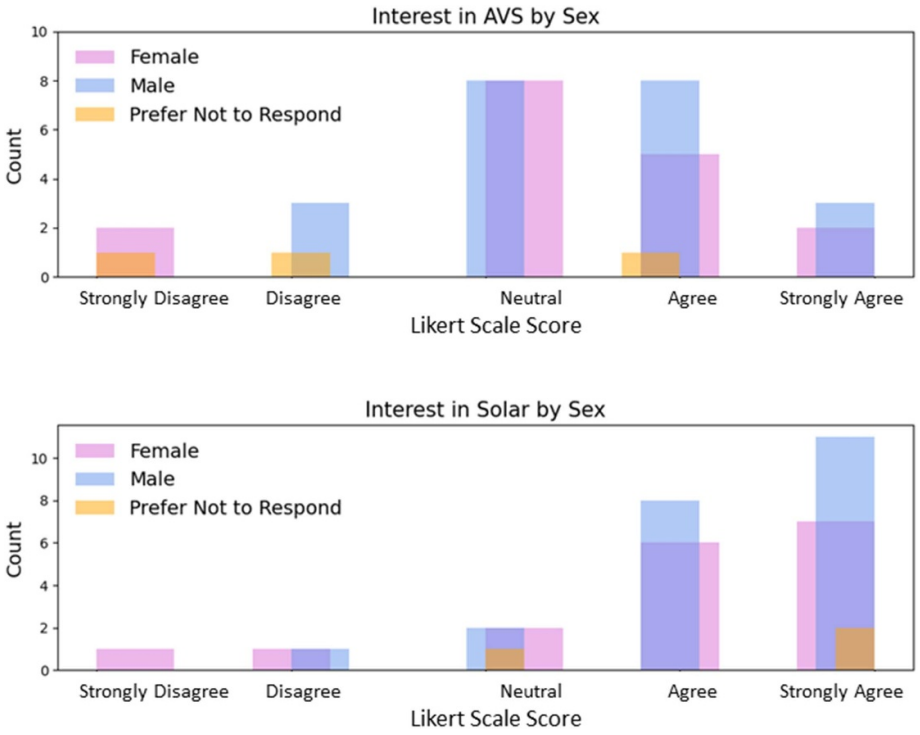


Figure A2. Interest in AVS (top) and solar broadly (bottom) by sex.

However, it should be noted that while the respondents evenly represented the two states, within the states they were concentrated to certain regions (appendix B, figure A3). Specifically, respondents were concentrated in Central California and the Piedmont region of North Carolina. It is possible that farmers in different parts of each state have differing priorities. For example, farmers in California's Central Valley may be more impacted by water use restrictions than elsewhere in the state. We did not have a sufficient number of respondents to evaluate potential differences at the zip code level.

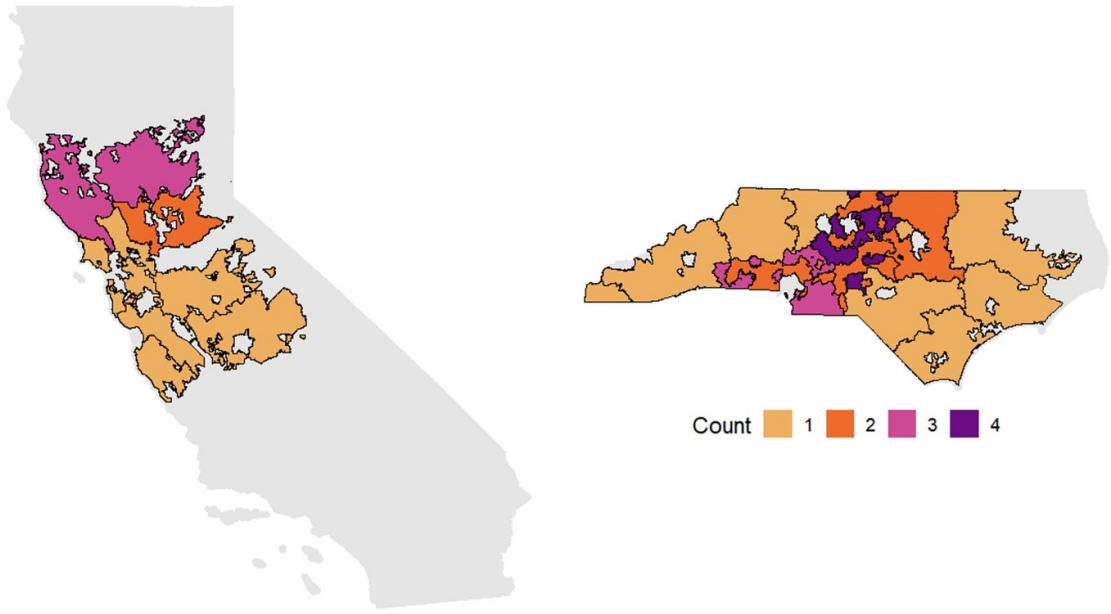


Figure A3. Geographic distribution of survey responses aggregated by the first three digits of zip code.

Participants also differed in what drove their farming decisions—a topic that emerged during the focus groups and was evident in the 'Other' factors listed as driving decision making (appendix B, table A3). Most participants identified their own personal preferences or experiences as driving their decisions, but environmental conditions, sustainable farming practices, and the needs of existing crops drove decision making for several participants.

Table A3. 'Other' influences on farming decisions.

Influence	Number of respondents
Personal preferences and experience	6
Weather, water, and climate	3
Beneficial environmental practices	2
Existing crops (e.g. orchards)	2
Ability to turn crops into value added goods	1
Staffing needs and training	1
Regulatory mandates	1

While figure 2 in the main text visually highlights the range of responses for the Solar/AVS block, the range for the remaining three blocks can be seen in figure A4 (appendix B). Interestingly, while respondents by and large felt similarly on questions related to Goals or Multiple Uses, they were far more split on questions in the Financial Risk block.

Because of the small sample size, these results are not statistically significant. However, analysis of responses to individual statements with interest in AVS, as seen in figure A5, highlights a few statements that merit further investigation. Namely, concerns surround the upfront cost of AVS; belief that AVS will increase profits; water reduction as a goal; and a belief that would diversify on-farm income. The key for the shorthanded questions can be found in table A4, below figure A5 (appendix B).

The four statements from the survey that were negatively worded (as seen in table A4) and recoded are:

- I am not interested in changing my farming choices even if it is equally costly
- I am not interested in changing my farming choices even if it saves me a little money
- I am not interested in reducing my farm's water usage even if I can afford it
- I cannot afford to make large capital investments in my farm



Figure A4. The distribution of responses to statements within the goals, financial risk, and multiple uses sections.

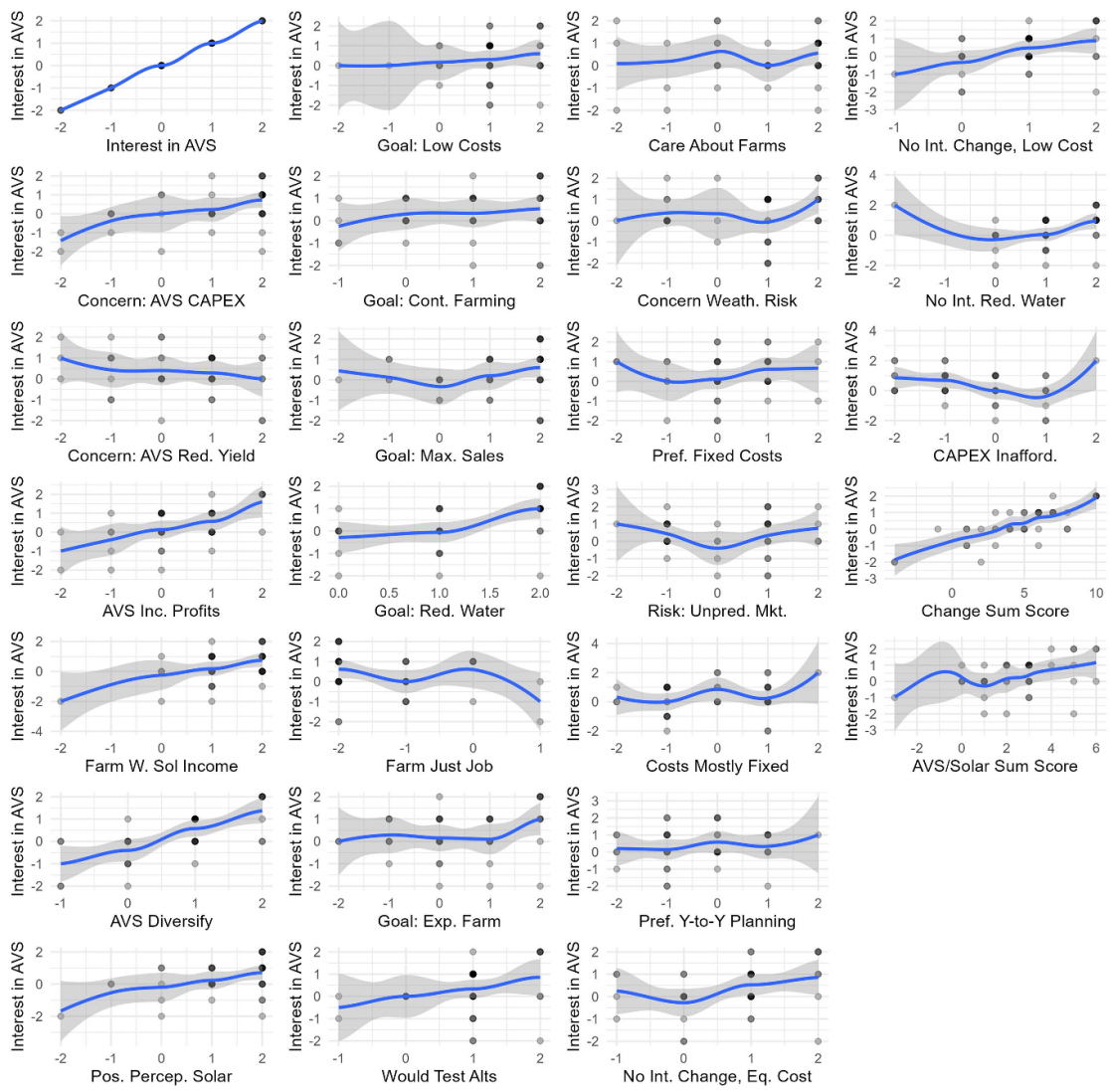


Figure A5. Associations between interest in AVS and other survey questions.

Table A4. Abbreviations for survey statements, as used in figure 4 (results) and A5.

Statement	Abbreviation
I would be interested in making my farm an agrivoltaic system	Interest in AVS
Upfront cost is the major factor in deciding whether I would install an agrivoltaic system	Concern: AVS CAPEX
I think adding solar panels to my farmland would help make the farm more profitable	AVS Inc. Profits
I would keep farming even if solar power provided me with enough income to live	Farm W. Sol Income
I think that adding solar panels to my farmland would diversify my farming income, reducing my risk	AVS Diversify
I have a positive perception of solar power	Pos. Percep. Solar
My goal is to lower costs	Goal: Low Costs
I want my children/relatives to continue farming	Goal: Cont. Farming
My goal is to maximize my farm's gross sales	Goal: Max. Sales
I care about reducing my farm's water footprint	Goal: Red. Water
Farming is just a job	Farm Just Job
I plan on expanding my farm	Goal: Exp. Farm
I am willing to use some portion of my land to test new technology and techniques	Would Test Alts
I care how many farms there are in my area	Care About Farms
Weather and water availability are the biggest risk to my farm income	Concern Weath. Risk
I prefer slightly lower, fixed revenues instead of unpredictable, but potentially higher, revenues	Pref. Fixed Costs
Market prices make my farm revenues unpredictable	Risk: Unpred. Mkt.
My biggest costs are fixed, or overhead	Costs Mostly Fixed
I prefer planning my crops on a year-to-year basis instead of long term	Pref. Y-to-Y Planning
I am not interested in changing my farming choices even if it is equally costly	No Int. Change, Eq. Cost
I am not interested in changing my farming choices even if it saves me a little money	No Int. Change, Low Cost
I am not interested in reducing my farm's water usage even if I can afford it	No Int. Red. Water
I cannot afford to make large capital investments in my farm	CAPEX Inafford.
I am worried an agrivoltaic system would reduce my crop yield	Concern: AVS Red. Yield
Summated scale for AVS and solar power	AVS/Solar Sum Score
Summated scale for 'willingness to change'	Change Sum Score

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