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Are long-term climate projections useful for on-farm adaptation decisions?

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The current literature on climate services for farmers predominantly focuses on seasonal forecasts, with an assumption that longer-term climate projections may not be suitable for informing farming decisions. In this paper, we explore whether certain types of long-term climate projections may be useful for some specific types of farming decisions. Through interviews with almond tree crop farmers and farm advisors in California, we examine how farmers perceive the utility and accuracy levels of long-term climate projections and identify the types of projections that they may find useful. The interviews revealed that farmers often perceive long-term climate projections as an extension of weather forecasts, which can lead to their initial skepticism of the utility of such information. However, we also found that when farmers were presented with long-term trends or shifts in crop-specific agroclimatic metrics (such as chill hours or summer heat), they immediately perceived these as valuable for their decision-making. Hence, the manner in which long-term projections are framed, presented, and discussed with farmers can heavily influence their perception of the potential utility of such projections. The iterative conversations as part of the exploratory interview questions, served as a tool for *"joint construction of meaning"* of complex and ambiguous terms such as "long-term climate projections," "long-term decisions" and "uncertainty." This in-turn supported a joint identification (and understanding) of the types of information that can potentially be useful for on-farm adaptive decisions, where the farmer and the interviewer both improvise and iterate to find the best types of projections that fit specific decision-contexts. Overall, this research identifies both the types of long-term climate information that farmers may consider useful, and the engagement processes that are able to effectively elicit farmers' long-term information needs.

KEYWORDS

climate change adaptation, long-term climate projections, farmer's decision-making, exploratory interviews, actionable knowledge, perennial tree crops, California, climate services

1. Introduction

As farmers across the world grapple with the impacts of climate change, there is an increased urgency to implement and accelerate agricultural adaptations (Howden et al., 2007; Hatfield et al., 2011; Pathak et al., 2018; Bezner Kerr et al., 2022). Information on expected future climate change can potentially assist farmers in making adaptive on-farm decisions that avoid the negative impacts of climate change, and take advantage of favorable conditions (Jones et al., 2000; Hansen, 2002; Prokopy et al., 2013; Mase and Prokopy, 2014; Ranasinghe et al., 2021). The growing scholarship on "climate services"[1] and actionable climate knowledge, has made several advances in understanding farmers' perceptions of climate forecasts, their specific decision-contexts, and providing them with tailored forecasts (Podestá et al., 2002; Vaughan and Dessai, 2014; Doll et al., 2017). For example, the literature has mapped and examined the many public and private sector agencies (at international, national, regional, and local scales) that have worked with users to contextualize climate knowledge for specific decision contexts (Vaughan and Dessai, 2014). Further, there have been advances in assessing the various sectoral challenges and benefits of using climate information (Hansen et al., 2011; Selvaraju et al., 2011). However, a majority of this literature currently focuses on seasonal forecasts, with only a handful of studies focusing on longer time-scales[2] (such as decadal or longer) (Hansen, 2002; Mase and Prokopy, 2014). This focus is partly due to the long-standing assumption that farmers typically plan on a year-to-year basis, and that there is not enough "certainty" in longer-term projections to be useful to farmers.

Focusing solely on seasonal climate forecasts without simultaneously thinking about longer time-scales can be problematic as some short-term coping mechanisms can preclude the ability to undertake more transformational adaptation strategies (Singh et al., 2018; Schipper, 2020; Berrang-Ford et al., 2021). Several scholars have argued that adaptation actions that do not consider long-term climate impacts are not likely to be effective (Adger et al., 2009; Dessai et al., 2009; Schipper, 2020; Berrang-Ford et al., 2021). Recent research, such as those on robust decision-making frameworks, flexible adaptation pathways and decision-scaling, suggests that despite uncertainties, long-term projections can still provide information on broad trends that help in better planning or preparation (Dessai et al., 2005, 2009; Lempert and Groves, 2010) as long as they are used in an appropriate and pragmatic manner. Such information can be useful for certain types of long-term decisions or adaptations e.g., risk management, planting locations, making larger capital investment decisions, choosing resilient crop varieties, etc. (Howden et al., 2007; Crane et al., 2010; Nicholas and Durham, 2012). The main argument is that informed decisions about an uncertain future may be better than uninformed decisions.

Long-term climate projections can entail a wide variety of information such as future trends in climate variables, likelihood of future extremes, or changes in crop-specific metrics (Singh et al., 2018; Vincent et al., 2020). Similarly, on-farm decisions can also be wide-ranging; from day-to-day management decisions to crop selection or land purchase (Howden et al., 2007; Nicholas and Durham, 2012). Despite this complexity and ambiguity about the different types of long-term projections and the decisions they can support, very few studies have interrogated the long-standing assumption that long-term climate projections are not useful to farmers. A select few studies have used surveys to explore the usefulness of long-term information more broadly, such as by looking at utility of "annual outlooks" or "longer-term outlooks" or "climate information" (Prokopy et al., 2013, 2017; Lemos et al., 2014b). However, not many have explored farmers' preference for information on specific long-term shifts in crop-specific climatic metrics or on other specific long-term trends or patterns that may be of local relevance.

Recent studies have also started to recognize that in order to better understand how farmers may incorporate such long-term shifts or projections into their cultural, cognitive and decision-making landscapes, more qualitative and ethnographic approaches are needed (Roncoli, 2006; Crane et al., 2010; Prokopy, 2011; Doll et al., 2017; Ranjan et al., 2019; Vincent et al., 2020). So far, ethnographic methods have mainly been used to further the research on seasonal forecasts, and not as much to interrogate the utility of long-term climate projections.

In this paper, we explore the utility of different types of long-term climate projections, for on-farm adaptation decisions, using the case of almond tree crop growers in California. Through a qualitative analysis of interviews with farmers and farm advisors, the paper explores how interviewees perceive the form, use and accuracy levels of long-term climate projections. Using interviews as a tool for "joint construction of meaning" (Mishler, 1986) of complex terms such as "long-term climate projections," "long-term decisions," and "uncertainty," this research attempts to identify the types of information that can potentially be useful for on-farm adaptive decisions.

1 Climate services is defined as the provision of timely, tailored information and knowledge to decision makers (generally in the form of tools, products, websites, or bulletins), which is an important part of improving capacity to manage climate-related risk (Vaughan and Dessai, 2014).

2 For the purposes of this paper long-term or longer-term projections are referred to as projections of climate at a decadal or longer timescales derived from global or regional climate models (i.e. Global Circulation models or GCMs).

2. Background and context

2.1. Almonds in California as the case study

This study focuses on almond crop farmers and farm advisors in the central valley of California. There are more than 1,250,000 acres and ∼6,000 growers of almond orchards in California making it the world's largest producer of almonds (Almond Board of California, 2016; California Department of Food Agriculture, 2021). Almonds are a long-lived crop with a lifetime of 25–30 years, and the crop does not provide a return on investment for 8–10 years after planting. Unlike annual crop growers who can change their decisions on when to plant or what variety to plant every year, perennial fruit crop farmers have a longer time commitment on decisions. Therefore, adoption of climate resilient crop varieties are far more difficult and slower (Lobell et al., 2006). Any changes in climate within the orchard's lifetime of 25–30 years can have an impact on crop yield. Specifically, varying late winter and spring weather conditions have been known to result in lower yields for almond trees (Luedeling et al., 2009a,b). Providing almond farmers with information on long-term climate projections can potentially help them make decisions on which crop varieties or rootstocks are better suited for the future, what additional costs they may have to incur on increased irrigation water, and whether and how they need to change their farming practices in the long-run (Luedeling et al., 2009a; Lobell and Field, 2011).

2.2. Knowledge gaps in understanding farmers' utility for long-term climate information

There are a few knowledge gaps in the literature. The first gap is that most of the literature on usability of climate information focuses on annual crop farmers (Mase and Prokopy, 2014), and not many studies examine perennial crop growers (Nicholas and Durham, 2012). In addition, most of our understanding of farmers' perceptions on climate information utility are based on research that focuses on seasonal weather forecasts which is a very different type of climate information (Hansen et al., 2011; Mase and Prokopy, 2014). Weather forecasts and climate projections differ both in the timescales they encompass, and in the form and type of information they provide. For example: daily or weekly weather forecasts can provide predictions of daily high and low temperatures or chances of rain. Seasonal forecasts or 30-, 60-, and 90-day outlooks (often also termed as long-range forecasts) usually provide probabilities of total precipitation and temperature departing from normal (Singh et al., 2018). On the other hand, long-term climate projections on decadal or 20–30-year time scales provide information on trends of increase or decrease in different climatic parameters, potentials of shift from historical conditions, etc. (Ranasinghe et al., 2021). The difference between long term weather forecasts and climate projections is important to note because the two types of information are fundamentally distinct, derived from different types of models, have different accuracy and uncertainties, and hence have varied usability or actionability. Therefore, research that focuses on weather forecasts might not be able to provide an accurate understanding of the actionability of long-term climate projections.

Another knowledge gap is that farmers' long-term climate information needs can be difficult to elicit, because they may not immediately know the types of information that could be most useful (Vincent et al., 2020; Jagannathan et al., 2021), and whether science can provide such decision-relevant information with reasonable skill (Roncoli et al., 2009; Briley et al., 2015; Porter and Dessai, 2017; Jagannathan et al., 2020). Crop-specific actionable climate projections (i.e., of crop-relevant climatic metrics, time scales, spatial scales) are not readily available in the scientific literature (Roncoli et al., 2009; Vincent et al., 2020; Vogel et al., 2020). Hence interpreting the potential utility of hypothetical projections can be difficult. Further, there are a large variety of farms and types of farming decisions, each requiring very specific types of climate information (Mase and Prokopy, 2014). For example, the information needed for deciding what crop varieties to plant, might be very different from information needed for managing pests and insects. There are also several different types of "long-term climate information" each with a different utility for the farmers/farming decisions (Hansen, 2002; Crane et al., 2010). For example, the utility of projections of agro-climatic metrics such as growing degree days or chill hours, may be different than projections of physical climatic metrics such as average seasonal temperatures, or changes in physical climatic phenomenon like El-Nino. Hence identifying which types of projections are useful and for what decisions, can be very challenging, and necessarily requires iterative interactions between scientists and farmers (Vincent et al., 2020; Jagannathan et al., 2021).

In addition to gaps in understanding the types of long-term information that can be potentially actionable to farmers, there are also gaps in understanding farmers' tolerance for uncertainties in long-term information (Nissan et al., 2019; Waldman et al., 2020). While many studies have found that farmers often find uncertainties in climate information to be prohibitive, these are also focused on seasonal forecasts (Mase and Prokopy, 2014) or a very specific type of long-term projection (Nissan et al., 2019). For example, studies have found that farmers may not find climate projections in the 10–30 year time scales useful since they do not sync with the observations in terms of timing of modeled inter-annual variations (Nissan et al., 2019). While such uncertainties indeed make the use of year-to-year climate data challenging, the climate model evaluation literature has shown that models are able to predict decadal trends and potentials for shifts from historical conditions, reasonably well (Lee et al., 2021; Ranasinghe et al., 2021). However, not many studies have explored whether information on crop-specific long-term trends and potential shifts would be useful to farmers. Overall, there is limited understanding on whether a farmer would prefer to know or not know about uncertain and imperfect long-term climate change projections. Considering the urgency for adaptation, and the long investment time frame of some of the decisions that farmers are making today (e.g., buying land or irrigation equipment), the preferences of the ultimate user and their perception of uncertainty would be crucial to understand.

3. Methods

Interviews were conducted with 11 farmers representing about 10,000 acres of almond trees across the central valley of California (8% of the total almond acreage of California), 5 farm advisors from University of California's Cooperative Extension (UCCE), and one member of the almond industry board. The interviews were conducted between January and April 2016, which was the last year of the 2011–2017 California drought. The sample of farmers was non-random and purposive, and they were contacted with the help of the UC cooperative extension. The sample included farmers of various age groups from late 20s to over 60s, farm sizes ranging from 60 to 4,000 acres, and farmers with over 40 years of experience as well as early farmers. Several of the farmers grew other tree and row crops in addition to almonds, although almonds were the major crop. The farm advisors who were interviewed, are experts in both research and bringing research to on-farm practice. They have advanced degrees in agriculture, pest management, soil sciences, etc., and varying levels of understanding of climate change and climate change projections. Farm advisors are considered as trusted advisors and key intermediaries or information brokers for climate information (Prokopy et al., 2013; Lemos et al., 2014b; Haigh et al., 2015). Hence their opinion on potential utility of climate information to farmers was also gathered. Two interdisciplinary climate adaptation researchers, one of whom is a climate adaptation expert with the UC Cooperative Extension, conducted the interviews. The two interviewers had expertise both in farmer decision-making contexts, as well as practical applications of climate model data.

Each interview was about an hour or an hour and a half long, where the objective was to gather rich and nuanced data on farmers' preferences for long-term information. The interview was semi-structured, but also included several exploratory questions that evolved during the course of the interview. The semi-structured interview guide included questions on key factors affecting farmers' decision-making, key issues faced by farmers in the last few years, farmers' use of weather/climate data in the past, the impacts of climate change they have experienced in the past, the climatic metrics that are of relevance to their crops, and finally the potential utility and use of different types of climate projections for decision-making (including perceptions of uncertainty, time-scales of relevance, preferred communication methods, etc.). While these broad themes remained the same, several questions during the interview were more iterative, and guided by the interviewee's answers. This was based on Mishler's interviews as a "joint construction of meaning" approach (Mishler, 1986), where both questions and responses on "potentially useful long-term projections" were developed and shaped by the discourse between interviewers and the interviewee. For example, in several interviews the farmers were asked about the utility of hypothetical long-term projections of certain climatic metrics. The actual climatic metrics presented during these discussions varied from farmer to farmer, as they were structured based on the metrics that the farmers themselves stated as being important for their crop. This approach was invaluable in the interview, as it allowed for contextualizing the projections to individual farmer's preferences (in a sense also jointly create new potentially useful projections), beyond just a few interviewer-driven projections. The interviews also involved a lot of clarifying, probing, iterative back-and-forth discussions, and mutual learning between the interviewer and the interviewee. For example, several interviewees asked the interviewers to help provide a better understanding of climate models, what they can predict, what kind of uncertainties there are, etc. And the interviewee was also probed with several different types of potential climate projections, to gather their comparative utility to the farmers. Such detailed two-way discussions were critical as it allowed for the interviewers to reformulate questions and respondents to reframe answers based on their reciprocal understanding as meanings emerged during the interview.

The interviews were audio-recorded, transcribed, analyzed, and coded thematically. Approval from University of California Berkeley's Human Subjects Committee Institutional Review Board was obtained for the interviews. Since the interviews were exploratory, our findings are focused on the qualitative aspects, and we do not present numbers for every section.

4. Results

4.1. Diversity in current use of weather and climate information

We started our interviews by trying to understand farmers' decision-contexts and their current use of weather and climate information. Overall, we observed a diversity in the ways that farmers used weather and climate information. Most farmers used real-time temperature, humidity, rainfall, and frost data—either from their own weather station, a CIMIS (California Irrigation Management and Information System)

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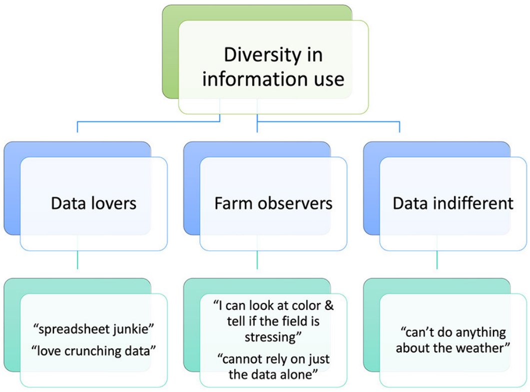

FIGURE 1
The diversity in how farmers used weather and climate information, along with illustrative quotes for each category. "Data lovers" based many decisions on detailed analysis of multiple data sets, wet ions. "Farm observers" often used data but preferred to make decisions based on their observations or visual monitoring of crop health and performance. They used data/information as an add-on to the visual signals they could observe. Finally, there were some farmers who were "data indifferent", who said that they monitor the weather for some critical parameters like extreme heat or frost but did not pay too much attention to data since there was not much one can do about the weather.

weather station near their farm, the farm bureau weather service, or from free online sources. This real-time data was used for computing irrigation needs, for anticipating frost protection measures, and identifying pesticide spray timings (based on rain). A couple of farmers used advanced monitoring systems for plant stress and soil moisture, but this was rare. In terms of forecasts of weather, some farmers bought custom frost forecasts for their regions (if they were in frost-prone regions), and many used online sources such as weather underground, weather channel, accuweather, etc. for forecasts of their weather. However, farmers varied in the extent to which they relied on and examined the data for making on-farm decisions. Figure 1 illustrates this diversity by showing three broad categories of how farmers used weather and climate data. We observed that most of the farmers we interviewed, only used weather information, and none used long-term climate information actively. A couple of farmers mentioned thinking about trends in the last 5-years "mentally," but such data was not actively incorporated into any decisions.

4.2. Initial perception of climate projections as an extension of weather forecasts

Some of the early interview questions were designed to understand interviewees' initial interpretations of the term "long-term climate projections." The interviewees were provided with a basic definition of weather vs. climate, and some examples. They were then asked whether they have used or will likely find use for "trends of or shifts in temperature or precipitation metrics in longer time scales say decadal or longer time scale climate projections." At this stage, most of the farmers perceived long-term projections to be similar to 30- or 90-day outlooks or El Nino forecasts but for annual or longer timescales. Based on this interpretation of long-term projections, many farmers suggested that they would not find such information useful as they were unsure of the skill of such forecasts. In the subsequent discussions it became apparent that the National Weather Service Climate Prediction Center's 30-day or longer outlooks, are commonly termed as "long-range forecasts" in the agricultural community, which then led to farmers conflating these with what the interviewer was calling "long-term climate projections." Therefore, although the farmers' initial reaction to long-term climate information was not positive, they were referring to seasonal or annual scale weather forecasts. The following quotes from farmers, further illustrate this point:

> *"No, I don't believe them {long-term projections} most of the time. This year they kept predicting there's going to be an El-Nino, well I probably believe that but it does not tell you if it is going to be a wet or a dry El-Nino, so we don't subscribe to those forecasts."* ***(Farmer 3).***

> *"Well, I still will look at that 45-day forecast, even though I don't believe it. Sometimes, it gives me a start, even if it is not accurate."* ***(Farmer 5).***

> *"In a year like this there was a lot of talk about El Nino so I looked at those and purchased a few more beehives this year, that's about as long as an outlook as I typically do, it is so difficult to forecast long-term."* ***(Farmer 2).***

This confusion was observed even with some of the farm advisors, who were aware of climate change impacts and issues. Two of the five farm advisors we interviewed, had worked with climate change projection data and hence understood the term well. Out of the rest, two advisors asked to clarify what the interviewer meant by long-term trends on temperature, and the fifth advisor conflated a long-term climate projection to a weather forecast at longer timescales. Initially Advisor 2 suggested that such climate change projections were not useful as it would be *"hard to base long-term capital investments on something that is still evolving as a science,"* and even equated basing decisions on long-term projections to basing investments on the predictions of the stock market. However, toward the tail-end of the interview, Farm Advisor 2 stated that long-term projections can be useful if presented as a *"potential for shifts"* in climate to occur.

This is when their preconceived interpretation of a climate projection became apparent. The below quote suggests that they initially interpreted long-term climate information as temperature on a certain day in 20 years—rather than perceiving it as a trend.

> *"It is not so useful that the prediction is that in the next 3, 4, or 10 years the temperature is going to be this, but that farmers practices must include the potential that there would be these shifts. I think that is a better argument, and farmers will respond to an argument like that, rather than saying hey, in 20 years the temperature is going to be 49 degrees on Feb 22 or something like that."* ***(Farm Advisor 2).***

In summary, the interviews suggested that both farmers and farm advisors tend to interpret long-term climate projections as extensions of weather forecasts. This interpretation, while not always incorrect, is not the type of long-term projections that can provide the best most skilled information to farmers about long-term changes, resulting in the interviewees questioning the accuracy of such information. Further, it reveals that farmers' and farm advisors' hesitation in using long-term projections could be conflated with their skepticism of seasonal or long-range weather forecasts rather than of the long-term GCM-derived downscaled projections in the form of trends or potentials of shift in conditions.

4.3. Climate impacts and metrics of relevance identified by farmers

Despite most interviewees' initial skepticism on the usefulness of long-term projections, when asked whether they have experienced any long-term gradual changes in climate such as warmer winters or lesser fog, all the farmers (without exception) and most of the farm advisors agreed that they have been seeing these changes. Most farmers identified specific changes in climate patterns as compared to the past and connected these changes to farm-level impacts (Table 1). They also suggested that these impacts were becoming regular phenomena. In terms of warmer winters and lower chill hours, farmers reiterated that this was less of an immediate issue for almonds which has lower chill hours requirement, but other crops such as some varieties of peaches, walnuts, and pistachios, have suffered due to reduction in chill hours and that it was likely to deter them from planting those again. While the farm advisors also agreed that farmers may be experiencing such impacts, they also suggested that understanding of these trends and impacts is not yet being incorporated in farmers' planning. Below are statements made by farmers on climate impacts:

TABLE 1 List of climatic changes and farm-level climatic impacts observed by farmers and farm advisors.

Climatic changes observed
• Warmer winters and lesser chill hours
• Drier winters (lesser rain during winter, lower snowpack)
• Lesser fog
• Warmer springs
• Increased summer heat (more days above 90 or 100°F)
• Reduced water levels
Farm-level impacts identified
• Decreased yield in crops like walnuts and pistachios due to lower chill hours
• Earlier blooms
• Flashier (quicker) blooms
• Advanced harvesting dates (quicker nut development)
• Changes in pest and disease regimes (evidenced by change in spray timings)

> *"It has been warmer the last five or so years, definitely. 80 degree days in February and 90 degree days in October, yes, clearly"* ***(Farmer 7).***

> *"In the last 4 years bloom has moved up, Harvest used to be toward the end of August now the norm in August 15th, it has been that was for the last 4–5 years. We have always had an early year in the past, but now it's like the early years becoming the normal."* ***(Farmer 5).***

The interviewees were then asked to identify key climatic metrics that were crucial for optimal growth of their almond trees. Table 2 shows some of these crop-specific metrics and related management decisions.

4.4. Crop-specific projections are very useful to farmers

One of the main aims of the interviews was to understand whether some specific types of projections may be useful to farmers, particularly those pertaining to crop-specific metrics that farmers identify as important. Hence the farmers were engaged in discussions of different types of "hypothetical" projections of crop-specific climate metrics. We used variations of the question *"if I could tell you something about how {XX metric} would change in the next 10–30 years, would that be useful."* These questions often manifested organically during iterative interactions with the farmers. Some examples were: "*if we could tell you that summer maximum temperatures may increase by say, 2–3°F in the next 20 years, would that be useful*

TABLE 2 Climatic metrics of relevance for the almond crop (along with potential impacts of these metrics on the crop and related management decisions) as identified by farmers and farm advisors.

Almond lifecycle stage	Climatic metric of relevance at each lifecycle stage	Potential impact of metric on crop	Management decisions relevant to the metric
Dormancy (Nov–Feb)	• Chill hours (# of hours in winter when temp is <45°F)	• Lower than necessary chill hours impact nut set and eventually crop yield	• Understand potential for good or bad crop • Identify if dormancy breaking measures such as spraying rest breaking agents may be needed • Examine viability of different crops or varieties (e.g., which tree crops to plant, or whether to invest in low-chill crop varieties)
Pollination and bloom (Feb–Mar)	• Optimal bee flight conditions (no rain, <10 mph winds, temp > 59°F) • Frost during bloom • Temperature during bloom	• Timing and effectiveness of bloom • Frost can cause crop loss or damage	• Evaluate number of beehives needed • Identify need for frost protection measures and investments (such as irrigation water or wind machines) • Consider early or late blooming crop varieties • Evaluate need for self-pollinating crop varieties (such as independence variety of almonds)
Maturing nuts (Apr–Jun)	• Summer heat [Max temp and Evapotranspiration (ET)] • No. of extremely hot days (>90 or 100°F)	• Impacts irrigation needs • Increases need for rapid water release • Changes harvest timings • Increases pests and disease threats	• Compute water and irrigation needs • Identify irrigation equipment needed for rapid release of water during very hot days (e.g., how many irrigation emitters of what size are needed) • Examine pesticide spray types, amounts and timings • Understand potential labor or work conditions impacts (due to heat) • Evaluate alternative heat or pest-resistant rootstocks
Hull-split and harvest (Jul–Oct)	• Occurrence of rains • High humidity occurrences • No. of extremely hot days (>90 or 100°F)	• Impacts harvest timing and operations • Increased pest or disease risk • Rains can cause nut damage • Humidity can cause hull rot	• Identify and plan for harvest protection measures • Plan for potentially changed harvest timings • Evaluate choice between various early or late harvesting varieties
Year-round	• Temperature and growing degree days (GDD) • Evapotranspiration (ET) • Humidity • Snowpack • Water availability • Soil moisture	• Impacts overall growth • Identify water needs	• Irrigation management • Overall crop monitoring

information to you" or "*based on climate model projections if we say that chill hours may continue to reduce by 5–10 chill hours into the next 10–20 years, is that information useful to you*." In many interviews, the metric of chill hours was used as a starting point, since one of the interviewers was most familiar with this data (Jagannathan et al., 2020).

As a stark contrast to the initial negative reaction to the utility of "long-term temperature projections" phrased more generically, when the interviewer discussed potential changes in crop-specific projections, all the farmers suggested that such information would "absolutely" or "definitely" be useful to them. In fact, all of the farmers we interviewed also suggested that depending on the rate of change, such projections may make them re-think the varieties or crops they plant, the way the manage their operations, and in some instances even prompt them to not plant certain crops. Table 3 presents a list of the types of climate projections that farmers identified as being useful or actionable for their decision-making. Some of the farmer's responses to these hypothetical projections are presented below:

> *"Absolutely {this information is useful}. I'm starting to recognize today just the difference in fog. When you see so much difference in a short amount of time in your immediate area, we're going to have to adapt varieties because this is a 20 or 25 year planting and we're going to have to find crops that or varieties that will adapt to that."* ***(Farmer 1).***

> *"I think it would be useful. Throughout our farm's history, we've grown more than 15 crops probably, because you adapt to whatever is best suited. So knowing what's going to happen or at least having a good idea, if you know something's going to be or won't be viable, then you're going to try to phase that out, and phase in something that's better suited."* ***(Farmer 8).***

TABLE 3 The types of long-term climate projections that were identified as actionable by farmers.

Types of long-term climate projections identified as useful by farmers
• Percentage change in chill hours (as compared to historical trends)
• Probability of "low chill" years
• Changes in temperatures during bloom (both average and maximum temp)
• Changes in spring temperatures (both average and maximum temp)
• Changes in frost timing during bloom
• Changes in number of frost occurrences during bloom (or likelihoods of frost)
• Number of extreme heat days in summer and fall (above 95 or 100°F)
• Overall change in summer or fall heat (average and maximum temp)
• Changes in fall rain timing
• Potential for rain occurrences during harvest (or number of rainy days during harvest)
• Rainfall trends
• Snowpack trends
• Drought occurrences
• Long-term changes in regional water availability

Farmers suggested that these types of projections would be useful to know for the next 10–30 years timescales.

For many metrics farmers suggested that the actionability of the information depends on the actual rate of change of the metric. In a discussion about July max temperatures, a farmer suggested that:

> *"Just knowing that temperatures are going to increase, I don't know what that's going to do to my trees. If the trees have plenty of water will they be stressed, or will they be fine? But if you say the temperature is going up by 10 degrees, then you will start seeing more diseases, and so I say what can I do to alleviate it, then its useful – maybe I can reflect the sunlight or move to Oregon {laughs}."* ***(Farmer 11).***

One of the most surprising findings of the interviews were that although all the farmers immediately took positively to discussions of the utility of long-term crop specific projection such as chill hours or summer heat changes, some of the farm advisors were a little more pessimistic about how farmers would receive this information.

> *"The utility probably depends on what they can do about it, some things are out of their control, they can't make it colder."* ***(Farm Advisor 4).***

> *"You know I think it is certainly useful and interesting, but at least to my understanding growers would prefer fixes. I don't think there are very many people out there who will base a bulk of their financial decisions on that long-term situation."* ***(Farm Advisor 2).***

4.5. Farmers' decision-making timescales and the confusion between day-to-day vs. long-term decisions

4.5.1. Current vs. future decision timescales

Our interviews, to a large extent, found that many decisions on the farm currently have shorter decision-making time scales of 6 months to 5 years. However, after the farmers were presented with the longer-term crop-specific climate projections, we observed that most of them were open to thinking about how they should manage or design their farm in the next 20–30 years based on the long-term information. Overall, our discussions showed that even if farmers have not planned for longer timescales in the past, climate change could prompt a change in these decision-making time scales, particularly for perennial tree crop growers. The following excerpt from a back-and-forth conversation with Farmer 2, exemplifies this intent to change.

> ***Farmer 2***: *"It is just so hard to look out into the future, I am more looking into the next 1–3 years rather than 10–20 years."*

> ***Interviewer***: *"But what about these gradual changes we talked about like winters getting warmer and seeing less fog."*

> ***Farmer 2:*** *"Now that can be concerning because we have crops in California for a reason and obviously if it starts getting too warm, too dry, too wet, you just can't grow the same crops obviously. So that is a concern. But how, how long until that happens, I don't know."*

> ***Interviewer:*** *"What if I tell you hypothetically that spring temperatures may go up by a couple of degrees in the next 10–20 years, would that be useful in your planning."*

> ***Farmer 2:*** *"I am really interested in that. But like I said, 1–3-year window is kind of what I look at right now. I really shouldn't be. Obviously, you're planting perennial crops, like almonds tend to be in the ground for 20–30 years, so maybe I should look further out."*

4.5.2. What decisions can projections be useful for?

There was also confusion about the specific types of decisions that could be informed by long-term projections, which subsequently impacted farmers' perception of the usability of long-term information. Farmers currently use weather forecasts for day-to-day operational decisions, such as when to irrigate, or when to turn on frost protection devices. Hence their initial expectation is that longer-term climate will also help with similar operational decisions but for 20 years from now. However, long-term climate projections are primarily useful for planning and broader farm development types of decisions such as what varieties to plant, where to plant, how to change farming systems, etc. and this distinction was not immediately apparent to farmers. Figure 2 illustrates this confusion with the example of a weather forecast vs. climate projection of frost, and the different decisions each can help with. Iterative discussions between the interviewer and farmer were able to clarify this confusion and prompted farmers to think about climate projections from a planning perspective rather than a day-to-day operational perspective, which subsequently impacted their perception of usability of the projections. In other words, just like the *form* of climate projections was perceived as an extension of weather forecasts, the *use* of climate projections was also sometimes perceived as an extension of weather forecasts. It also showed that just like the term "long-term climate projections," the term "long-term decisions" was equally ambiguous and vague, as there was a confusion as to whether it meant an operational decision 20 years from now, or a completely different planning decision considering changes in the next 20 years. The following interaction with farmer 6 highlights this confusion between day-to-day vs. long-term decisions, and its relationship with the perception of usability of long-term information.

> ***Interviewer:*** *"If there was some long-term information about likelihood of increase or decrease in patterns of rains in March or perhaps increase in summer or July temperatures in the next 20–30 years, would that be useful to you?"*

> ***Farmer 6:*** *"Oh definitely, let's say if we knew that in some year it was going to have a lot of unsettled weather in February and March in time for me to order bees, instead of two hives per acre I would order three hives per acre, but I cannot do that with like a week's notice. I need to know beforehand."*

> ***Interviewer:*** *"Oh, but that might be a bit difficult, because the 20-year projections usually provide long-term trends and they may not be able to get the year-to-year very accurately. So, they may say for example that by 2036 you might see an increased likelihood in March rains or something but not really say exactly what will happen in 2030 or 2031."*

> ***Farmer 6:*** *"Oh I see."*

> ***Interviewer:*** *"So they may not be able to help your short-term decision on whether this year you will need more beehives, but they can help plan the range of number of beehives you may require in the next 10–20 years."*

> ***Farmer 6:*** *"Well, I think it still applies. I might say well maybe I should be thinking about having more bees. In fact, maybe I should buy another spray rig because there is going to be shorter windows when I have to spray quickly {because we may see rains}, that is certainly something I need to plan long-term. Also, maybe the next orchard I plant is a variety that is blooming later. So, there could be implications."*

4.6. Uncertainties in long-term climate projections

One of the goals of the interviews was to probe farmers about their opinion on uncertainties in information, through a series of simple questions. While this extremely simplified questioning about uncertainty thresholds of farmers is by no means an exhaustive study in the matter, the responses from the farmers were still very useful to shed light on their broad perceptions.

4.6.1. Utility of projections despite uncertainties

During our interviews, the interviewer transparently communicated to the farmers that the projections of climate were not 100% accurate due to the uncertainties in climate modeling, and unknowns regarding carbon emissions and other parameters. The interviewer then asked the farmers whether they were likely to use the long-term projections if there was only a 70 or 60 or 50% likelihood or confidence in such numbers. Surprisingly, almost all the farmers suggested that they understand that all future projections come with uncertainty and 70% and sometimes even 60% likelihood numbers would still be useful.

> *"If you put out confidence levels, I think everybody can evaluate for themselves. You don't have a crystal ball, but you can certainly extrapolate from the trends you are seeing. Sure."* ***(Farmer 3).***

> *"The thing is that you never make a decision off of one piece of information. There's a whole lot of information that goes into a decision like that. So would that {60% likelihood information} be in the mix? Yes. Would it be at the top of the priority? I would say no."* ***(Farmer 2).***

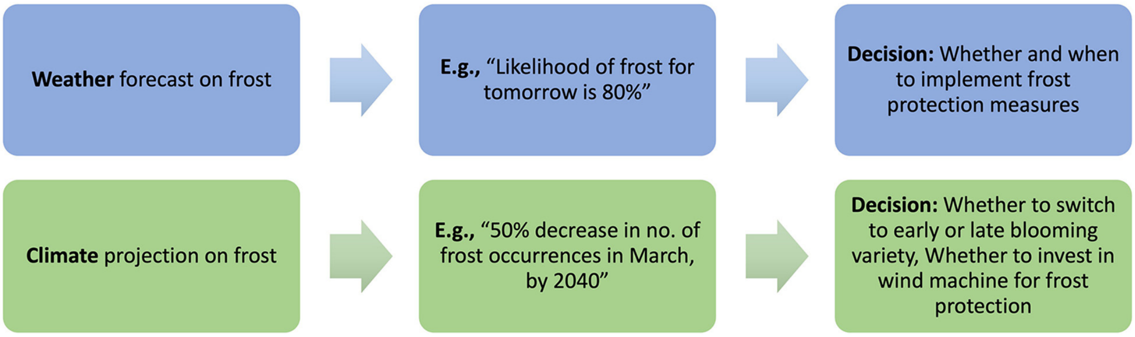

FIGURE 2
Figure illustrating the different between the form and use of a weather forecast vs. a climate projection for frost.

The in-depth discussions revealed that farmers and farm advisors perceived accuracy to be a key issue for short-term or day-to-day decisions, but for longer term planning decisions they were more tolerant toward uncertainties. Advisor 3 suggested that a 20% error in weather forecasts of frosts could mean complete crop loss, but if one is talking about changes in likelihood of frost occurrences over time then there is a bit more room to work with uncertainties. Farmers pointed out that their longer-term planning decisions are often dependent on several climate and non-climatic variables, many of which are uncertain (like market prices), so they understand and work with such uncertainties all the time. The interviews also showed that farmers would still like to know "uncertain" impacts or projections as long as the uncertainty ranges were transparently communicated. In fact, one of the advisors even cautioned against providing projections that seemed too accurate, to avoid a *"boy who cried wolf situation,"* because farmers were aware that such absolute certainty may not be possible in the long-term.

4.6.2. Utility of year-to-year values vs. trends

In our interviews we asked farmers whether projections would still be useful if they could only provide information about long-term trends, but not year-to-year absolute values. Many farmers suggested that information on trends would be preferred for long-term planning purposes.

> *"I think trend is more important than any specific point in time." **(Farmer 11).***

> *"I think trend will be good and useful because for long-term planning you have to kind of guess and anticipate as best you can." **(Farmer 8).***

Often, this discussion would prompt the farmers to ask the interviewers to explain what the models did and why such uncertainties existed. These discussions showed farmers' interest in learning more about the models, and not only helped clarified model capabilities (in very broad terms), but in several cases also allowed farmers to empathize with why it was not possible to provide very accurate year-on-year projections in the long-term.

4.6.3. What is more accurate: 10- or 20-year projections?

Another interesting finding from the interviews was that many farmers and even some farm advisors suggested that they preferred shorter timescale information because they assumed that 5- or 10-year climate projections are likely to be more accurate than longer time scales. Hence, their perception of accuracy of climate projections was also an extension of the accuracy of weather forecasts where accuracy decreases with time. However, climate models work differently from weather forecasts, and often 5–10-year times scales (due to internal variability of climate) are less accurately captured as compared to broader trends in 20–30 years where the internal variability smoothens out (Hawkins and Sutton, 2009). When this was communicated to the farmers, they suggested that they would prefer to use the more accurate 20-year projections. Hence there seemed to be a trade-off between the preferred temporal scale of information and its uncertainty. The following conversation with Farmer 4 sheds light on this.

> ***Farmer 4:** "Well personally I may look at all, but if there is something we can look at more accurately in the 5 or 10 years model then that's good, but I will be interested in the 20 years model too even if that's where things may get a bit leery because so many things change the further you go in time."*

> ***Interviewer:** "Well, that may not necessarily be true because the way these climate models work, we may actually be a bit more confident and see more of a signal on the 20 years time scale for trends anyway."*

> ***Farmer 4:*** *"Oh that's good to know that explanation has to be given, people are not going to know that right off the bat. And in that case that is more useful."*

5. Discussion: Co-constructing potentially useful "long-term projections" with farmers

A large portion of the literature that assesses farmers' perception of climate information, dismisses the potential use of long-term climate projections suggesting that farmers do not plan for such timescales, find such information to be too uncertain, and hence are not likely to use such information. Yet, most of these studies base their results using surveys as the sole instrument of study (Crane et al., 2010; Prokopy, 2011; Mase and Prokopy, 2014) and very few interrogate why farmers' have these perceptions, and whether climate change impacts may alter some of their current perceptions and decision-making patterns (Waldman et al., 2020). Through in-depth interviews with almond farmers and farm advisors in California, we find that the terms "long term projections," "long term temperature trends," "long term decisions," "uncertainty," etc., are complex and often ambiguous with multiple conflicting interpretations and meanings. Farmers initially perceive long-term climate projections as extensions of weather forecasts even though the two differ significantly in their form, type of use, and uncertainties. This mismatch in researchers' vs. farmers' interpretation of basic terms such as "long-term climate projections" is not well interrogated in the literature (Briley et al., 2015). The interviews illustrate that understanding and interrogating this mismatch is essential. Without such interrogation, there is a high possibility of misinterpreting farmers' utility of climate projections, by equating their perspectives on what they understand to be climate information (which is often seasonal forecasts) rather than their perspectives on the actual utility of long-term crop-relevant shifts and trends that climate projections can offer. Overall, our research provides rich empirical evidence to show how using surveys as a sole instrument can be limiting or even problematic, and reaffirms calls from other researchers on the need to incorporate more qualitative and ethnographic approaches in climate services research (Prokopy, 2011; Doll et al., 2017; Ranjan et al., 2019; Vincent et al., 2020). While our results are based on a small number of rich interviews with perennial tree crop farmers, more research is needed on how such misinterpretations might manifest for other types of farmers (such as annual crop growers) and impact the utility of long-term information.

The iterative nature of the interviews enabled the interviewer and interviewee to co-construct meanings for several terms related to long-term climate projections, which enabled the emergence of a shared understanding of what useful projections may look like, how they may be used, and what their uncertainties might be. This process clarified three key aspects of long-term climate projections: (1) climate projections were not the same as a weather forecast in the next 20–30 years, but rather provided information on trends or potentials of shifts from historical conditions, (2) projections are most useful for making long-term planning decisions on the farm rather than day-to-day or short-term operational decisions for several years from now, and (3) projections of climatic trends for 20–30 year time scales were likely to be more accurate than shorter time periods (unlike the accuracy levels in weather forecasts that tend to decrease with time). This clarification of the form, use and uncertainty of long-term climate projections was the critical turning point of the interviews. The trajectory of the interviews, and consequently farmers' perception of the utility of long-term climate information, completely changed once the farmers understood these three characteristics of long-term climate information. Further, when provided with narratives of potential future shifts in crop-specific metrics such as chill hours or summer extreme heat days, the perception of utility of the information enhanced even further since the farmers recalled having experienced such shifts in the recent past as well (Hackenbruch et al., 2017; Vincent et al., 2020; Jagannathan et al., 2021). These results have some parallels with prior studies that have found farmers are more likely to trust (and use) seasonal forecasts when they are facing impacts such as drier climate (Gunda et al., 2017; Waldman et al., 2020). Our interviews, similarly, showed that farmers were open to changing their decision-making time scales and practices when presented with potential long-term climate impacts. Hence considering farmers' current decision-making time scales and practices as fixed and immutable, may be limiting, as it does not acknowledge farmers' agency and willingness to change their practices in response to climate impacts.

As farmers started to understand the meaning and use of long-term projections, toward the tail-end of the interviews, many of them came up with newer uses of long-term projections that the interviewers had previously not thought about. Crane et al. (2010), term this as a process of "skilling" where farmers creatively employ new information streams within the context of their specific circumstances. Our iterative discussions not only led to a change in perception of utility, but also in "skilling" and mutual learning in identifying specific actionable long-term projections from a farmers' decision perspective. Table 4 provides example quotes from one farmer who was initially dismissive of long-term projections, and toward the end of the interview not only changed their mind on the utility of such information, but also identified several novel uses of such projections.

Finally, the interviews also found that several of these challenges and ambiguities in interpretation were not unique to farmers but were also prevalent with farm advisors. This highlights the complicated nature of the topic, and the need for

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TABLE 4 Additional quotes from farmers that exemplify how they identified novel uses for projections (despite uncertainties), and their need for information that allows to plan for the long-term.

Additional quotes from farmers
Examples of farmer identifying novel uses for projections
"Well one thing that when we talked about summer heat and your long-term forecast, let's say you're saying it's going to be this much hotter for longer time, then maybe I need to manage my irrigation such that I need to deliver water more rapidly so maybe I invest in two one gallon emitters instead of two half gallon irrigation emitter. So your forecasts can be making me make those changes if I could see that 10 or more years ago." (Farmer 5)
Farmers explain their need for information that allows them to plan for the long-term
"One of my biggest fears is that we will say ok we now have limited water supplies during the summer. So we're going to take that water for the cities and for the fish. If that's what society wants to do, that's fine. But I've invested in developing an orchard that I have been counting on getting the income back over 25 years. If you say you are turning the water off tomorrow, I'm screwed. But turning the water off slowly over the next 25 years, I can make capital decisions accordingly. We are not getting this information from anywhere." (Farmer 11)
"At least here in this area, we would like to know things as far in advance as possible. Almonds are looking at a lifespan of 20–30 years, and at the end of its life cycle, if it's going to be, if it's not going to be suitable to plant something else that I need to come up with a plan to plant something else. But it is not always that easy just to switch your operations, you know, maybe you might have to invest a lot of capital to, to grow something else, you need equipment you need and then you don't have expertise in it either, which is almost invaluable and takes time to build." (Farmer 8)

more open-ended conversations and clarifications to understand the actual potential of long-term climate information to inform adaptive decision-making. The findings also showed that farm advisors were more pessimistic about farmers' perception of utility of long-term information, than the farmers themselves were. This is perhaps because long-term climate projections are often discussed with farmers alongside discussions of anthropogenic climate change (Grantham et al., 2017). Some recent studies have also suggested that farm advisors are often worried about how their clientele will react to climate change information and hence are reluctant to engage in discussion of adaptive measures with them (Grantham et al., 2017; Kearns, 2021). In this research, the interviewers took cues from earlier work (Arbuckle et al., 2013; Doll et al., 2017) that suggests that one can have fruitful conversations about adaptation and the use of climate projections, without debating the human causes of climate change. Our findings here, differ from other studies that focus on corn crop advisors in the Midwest, where it was seen that advisors were more likely to show positive attitudes toward climate change adaptation than farmers (Lu et al., 2021), showing that there may be interesting regional and crop-based differences in attitudes of farm advisors. Training farm advisors on not just the potential uses of climate change projections, but also on how to engage in such mutually beneficial "joint construction of meaning" conversations on climate change, may be crucial to improve the understanding of the types of long-term information that can aid farmers in agricultural adaptations (Prokopy et al., 2013; Haigh et al., 2015; Kearns, 2021).

While this research points to an overall potential for long-term information to be useful for farmers, it is to be noted that the actual utility will greatly depend on the extent to which scientists and boundary agencies can effectively develop, translate and communicate user-relevant long-term climate projections (Lemos et al., 2014a; Goodrich et al., 2020; Kearns, 2021). While some types of potentially useful climate projections such as trends in temperatures may be easier to develop and communicate, other specific projections such as area-specific rainfall trends, or frequency of extreme events, may be more difficult. Despite these scientific limitations, this research shows that some farmers may still want to know about "uncertain" projections (communicated transparently with their errors and confidence levels) due to its potentially high impact on their planning and operations (Table 4).

6. Conclusions

The interviews uncovered farmers' perceptions on long-term information, uncertainty in projections, and potential use of such information for on-farm adaptations. The iterative format enabled clarifying discussions and mutual learning between the interviewers and the interviewees and led to "joint construction of meaning" of various complicated concepts and terminologies, through iterative adjustments and improvisational responses between the interviewer and interviewee. This eventually enabled the joint identification of the types of climate projections that can potentially assist perennial tree crop growers' in making different types of long-term management and planting decisions. These results highlight the importance of, and even necessity for, using qualitative in-depth discussions to appropriately understand farmers' perception of long-term climate information. It further suggests that the mismatch between farmers and researchers' interpretation of long-term projections, its accuracy, and its potential use, could perhaps be the reason for farmers not recognizing the utility of long-term climate projections. While our research focuses on perennial tree crop farmers in California, more such exploratory, rich, and probing conversations with different types of farmers can help in better understanding their use for long-term climate projections.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by University of California Berkeley's Human Subjects Committee Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

KJ and TP led the study conception and design and conducted the interviews. DD provided expert guidance on interview design and recruitment of interviewees. KJ led the data analysis and interpretation of results with feedback from TP and DD and drafted the initial manuscript. All authors reviewed and approved the final version of the manuscript.

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Conflict of interest

DD was affiliated with Division of Agriculture and Natural Resources, University of California, Davis, at the time that the research was conducted. He is now affiliated with Rota Unica Agriculture.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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