frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 04 July 2025
DOI 10.3389/fenvs.2025.1605176

OPEN ACCESS

EDITED BY
Prakash Kumar Jha,
Mississippi State University, United States

REVIEWED BY
Josef Křeček,
Czech Technical University in Prague, Czechia
David Lieske,
Mount Allison University, Canada

*CORRESPONDENCE
Tapan B. Pathak,
tpathak@ucmerced.edu

RECEIVED 02 April 2025
ACCEPTED 16 June 2025
PUBLISHED 04 July 2025

CITATION
Ikendi S, Lyons A and Pathak TB (2025) Advancing decision support for climate adaptation in agriculture and natural resources. *Front. Environ. Sci.* 13:1605176.
doi: 10.3389/fenvs.2025.1605176

Advancing decision support for climate adaptation in agriculture and natural resources

Samuel Ikendi[1], Andrew Lyons[1,2] and Tapan B. Pathak[1,3]*

[1]University of California, Division of Agriculture and Natural Resources, Davis, CA, United States, [2]Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA, United States, [3]Department of Civil and Environmental Engineering, University of California, Merced, CA, United States

Climatic changes in California require farmers to develop adaptation strategies to sustain their production. Decision support is a key element of climate adaptation but requires a robust understanding of producer needs and priorities. One approach to sharing adaptation information and gathering stakeholder interests and needs is through workshops. This investigation was conducted among 78 technical service providers in a session on adaptation decision support during the 2023 California Adaptation Forum. We adopted a constructivist orientation to understand stakeholder interests and needs on decision support during a 30-minutes dialogue. Four questions were discussed, and participants recorded their responses on different colored sticky notes which were analyzed thematically. Five interrelated themes were uncovered relating to the lived experiences of service providers in making decisions including climate impacts, community engagement and equity, adaptation programs, resources, and cost-benefit analysis. In making those decisions, the most used information sources and tools were community and tribal knowledge, reports like climate assessment reports, and specialized data portals such as Cal-Adapt, CalEnviroScreen, and Healthy Places Index. Several interconnected themes emerged around stakeholder perceptions of gaps in existing decision support resources, the relevance of decision support, and what researchers should focus on. These themes underscore the importance of data translation, visualization, and community engagement to harness stakeholder lived experiences, dissemination, and training to improve data access. We conclude there is a need to engage technical service providers in extension programs on adaptation decision support, equip them with necessary tools such as curricula and resources that will help in advising.

KEYWORDS

climate adaptation, decision support tools, visualization, tribal knowledge, translation, dissemination, community engagement, California Adaptation Forum

1 Introduction

California is the number one agricultural state in the United States, with a combined farmgate revenue of $59 billion from farms, ranches, and plant nurseries (California Department of Food and Agriculture, 2023a). The Mediterranean and unique regional and local climate zonation of California support the production of over 400 different crops including 40 specialty crops, 19 of which are not produced anywhere else in the country (Ikendi et al., 2024a, p. 2). Overall, the top crops that made up the largest share of the cash

value include grapes, miscellaneous crops (which includes nursery and greenhouse crops), almonds, lettuce, berries, pistachios, tomatoes, carrots, rice, oranges, floriculture, broccoli, tangerines, and lemons (California Department of Food and Agriculture, 2023a, p. 6). The diverse landscape of California also supports a flourishing high-value livestock and rangeland industry across the Mediterranean grasslands, woodlands, and chaparral; cold desert steppe; and warm desert rangelands (California Cattlemen's Association, 2023; Roche et al., 2015). Dairy products like milk, cattle and calves, broilers, hay, chicken eggs are among the top high-value commodities from California livestock and rangeland operations (California Department of Food and Agriculture, 2023a, p. 6).

Given the large-scale agricultural production in California, climate smart agricultural practices are vital to the state's agricultural, economic, and environmental security (Ikendi et al., 2024a; Lewis and Rudnick, 2019). However, the current and projected climate risks until the end of the century pose significant challenges to California's production potential (Pathak et al., 2018). Increasing frequency and intensity of climate-related stressors relating to increasing temperature, reducing water resources, and disasters such as dust storms (Adebiyi et al., 2025) and their associated impacts like increases in weed, pest, and disease pressures are already significantly impacting the broader economy (Jha et al., 2024; Parker et al., 2020; 2022; Swain et al., 2020; Roche, 2021; Skendžić et al., 2021; Zhang et al., 2021).

Farmers (Ikendi et al., 2024a; Kanter et al., 2021; Taku-Forchu et al., 2024) and ranchers (Munden-Dixon et al., 2018; Pinzón et al., 2025; Roche et al., 2015; Woodmansee et al., 2025), including those who are socially disadvantaged, beginning, and/or resource limited are under constant pressure to adjust to uncertain weather and climate events to minimize production risks. There is an increased demand from these producers to get locally relevant information on climate-related impacts and adaptation resources that serve their needs. Similarly, the Extension technical service providers such as federal and state agencies, universities, Cooperative Extension, natural resource managers, and crop consultants also have to deal with questions related to climate and weather variability, and their implications on farm operations and the environment. However, these service providers are often ill-equipped with locally relevant adaptation and mitigation resources to assist farmers and ranchers in implementing those decisions (Grantham et al., 2017; Johnson et al., 2023).

One of the climate smart agricultural strategies is advancing the use of climate adaptation decision-support information sources and tools designed to translate climate information into forms that support production decision-making (Ikendi et al., 2024b; Lieske, 2015; Lu et al., 2021; Pathak et al., 2023; Ranjan et al., 2020; United States Government Accountability Office, 2014). Growers have expressed a need for specific climate information that can serve their unique farm and ranch operations and also for rendering technical assistance in their communities (Jagannathan et al., 2023). Statewide stakeholders' needs assessment studies conducted on climate decision support information sources and tools in California revealed that the use of these sources and tools was overall less than 50% and further low among ranchers and extension technical service providers (Ikendi et al., 2024b). Moreover, these studies further found that farmers and ranchers used different decision support tools other than those used primarily by their advisors.

Collectively these studies highlight the need to uncover the lived experiences with decision support tools for climate adaptation in agriculture focusing on the Extension technical service providers. To better understand and address both successes and gaps, this investigation leveraged a large gathering of adaptation professionals to engage in a focused dialogue around decision support needs and opportunities.

1.1 Description and main aims of this study

This investigation was embedded in a Decision Support Tools for Climate Adaptation workshop during the 4th California Climate Adaptation Forum. The conference was organized by CivicWell and the Governor's Office of Planning and Research between July 31st through August 2nd of 2023 in Pomona, Los Angeles California. The 2-hour workshop was facilitated by six presenters from diverse institutions and agencies including the University of California Agriculture and Natural Resources/Cooperative Extension, California Department of Food and Agriculture, California Department of Water Resources (DWR), and California Pistachio Research Board. The workshop began with presentations from the facilitators around the work their organizations have been engaged in to support adaptation and decision support (Table 1).

The second half of the workshop involved an investigation where participants moved into breakout discussions to have a dialogue around decision support for climate adaptation. The discussions were structured around four questions with the overarching goal of understanding the interests, needs, and recommendations of the stakeholders for advancing decision support. The four questions discussed include:

1. What kind of decisions or issues do you face in your work related to climate change?
2. What information sources do you currently turn to, to help you make these decisions? Where are the gaps or shortfalls in those information sources?
3. How could adaptation information tools be more relevant and accessible to you and the groups you serve?
4. What can researchers do to help improve decision support for climate adaptation?

2 Methodology

A case study design was employed as a research methodology in this investigation, viewing each participating member as a case (i.e., a unit of analysis) which, in turn, allowed us to collect and analyze data on an individual basis (Creswell and Poth, 2018). Further, we utilized a cross-case approach to data analysis considering our participants as members of a community (i.e., a bounded system). The total number of participants were 78, mainly Extension technical service providers. The majority (48.7%, n = 38) were from private organizations, such as, Climate Science Alliance, Institute for Sustainable Communities, Rise South City, and Fernandeno Tataviam Band of Mission Indians; government

TABLE 1 Description of the themes presented on climate adaptation decision support tools.

No.	Themes	Description of the themes
1	Decision support for climate adaptation	Described climate change scenarios and their impact on agricultural production and human health; the impact and adaptation models scientists are creating and how decision support bridges these models to enhance climate resilience
2	Urban heat island and climate-resilient trees	Centered on progress made from research to implementation relating to cooling urban heat islands with climate-resilient trees across the cities in California
3	Vulnerable communities platform	Examined the climate decision systems: developments seen in California and the road ahead for agriculture using vulnerable communities platform indices, climate modeling, and creating a Cropping Climate Atlas
4	California Pistachio Research Board	Discussed the climate adaptation in California agriculture using lessons from Pistachios and how commodity boards support climate research efforts for scientists and farmers
5	Water resources management	Examined the climate action plan and DWR's comprehensive response to climate change emphasizing the three phases. Phase I: Greenhouse gas emissions reduction plan; Phase II: consistent, high-quality climate change analysis across all DWR programs; and Phase III: vulnerability assessment and adaptation plan. Provided the DWR's recommended research priorities for California's 5th climate change assessment
6	CalAgroClimate tools	Described and illustrated an array of online decision support tools relating to heat, frost, pests, crop phenology, and agroclimatic indicators that support climate risk management

entities (42.3%, n = 33), such as, City and Port Authorities, Departments of Water, Transport, Health and Food, and Governor's Office of Planning and Research; and University Academics and Cooperative Extension Advisors (9.0%, n = 7).

2.1 Data collection

We followed the rules of natural setting aiming towards our topic and objectives of the investigation, session, and forum (Creswell and Poth, 2018; Rossman and Rallis, 2017). A rapport was first established through a warm welcome, introduction of the session agenda, and speakers and highlighting the need for feedback during the breakout session. The session was organized as a workshop but equally as a listening session to understand the interests and needs of the stakeholders, and how they are thinking about decision support for climate adaptation. Responses were collected from a set of four questions with facilitation from the research team during the dialogue. To ease the discussions and collection of responses, questions were displayed by a projector–one question at a time, and participant responses were recorded on different colored sticky notes during the discussions.

Each colored sticky note had a specific question(s) as follows, Green: What kinds of decisions or issues do you face in your work related to climate change? Pink: (part a) What information sources do you currently turn to, to help you make these decisions? and a follow-up question (part b) Where are the gaps or shortfalls in those information sources? Orange: How could information tools be more relevant and accessible to you and the groups you serve? Blue: What can researchers do to help improve decision support for climate adaptation? Each question was clearly articulated when facilitating the discussions using the art of probing participants to gain further clarification as well as providing rich information on the study topic. Caution was exercised during discussions, not to be judgmental about participants' views during the discussions to facilitate the natural flow of conversations (Creswell and Poth, 2018; Rossman and Rallis, 2017). Memos and field notes were taken during discussions after which all sticky notes were collected.

2.2 Data analysis

All sticky notes were arranged by their colors and counted as follows: Green (n = 45), Pink (part a, n = 41; part b, n = 39), Orange (n = 41), and Blue (n = 40). As a caution, the value of "n" represents the number of sticky notes and may not be exactly the number of respondents (i.e., some participants may have written responses for the same question on more than one sticky note). We took a quick scan and read all the responses from each sticky note while meditating on those responses relative to the presentations of the guest speakers, the discussions in the breakout session as well as writing analytic memos (Lincoln and Guba, 1985; Saldaña, 2024). After a quick read through the sticky notes, one member of the investigation team assigned serial numbers to each sticky note to ease referencing during cross-case comparisons. The responses were typed in a Microsoft Word document following their assigned serial numbers and by their colors (see Supplementary Material for the raw responses). The transcripts were shared with the investigation team to facilitate an additional engagement in a dialogue with the data to process its meaning.

Generating meaning from the transcribed data was done inductively by reading the transcript word by word and line by line for a particular question and developing codes after which the codes were merged into major themes (Lincoln and Guba, 1985; Saldaña, 2024). In the process of coding and thematic analysis, we sought to recognize and classify commonalities across the experiences of participants on climate decision support and perspectives that appeared distinct among cases. We triangulated our data with the memos written during data collection (i.e., field memos) and analysis (i.e., analytic memos) that helped us to reflect on emerging unique themes and ideas from the data. We shared our themes amongst ourselves and held three meetings (and several email correspondences) to discuss the thematic findings and their meaning to help in making reasonable discussions and conclusions that reflect the findings of our investigation and their implications on the use of decision support for climate adaptation.

The findings are presented thematically in tables and pie charts based on the question and the relative number of codes (frequency and percentages) aligned by the themes to depict the predominant themes among cases on each question. Findings are also elaborated in rich thick descriptions as well as participants' verbatim statements extracted from

TABLE 2 Decisions or issues stakeholders make or relating to climate.

Theme	Examples of codes
Equity	Social justice, equity, inclusion, social vulnerability, mistrust, relationship, community, and collaboration
Adaptation programs	Programs, prioritization, data translation, sustainability, tree planting, information, and technology
Climate impacts	Greenhouse gas, heated cities, mental health, violence, flood, sea level rise, species decline, migration
Cost analysis	Costs-benefit, projections, opportunity cost, investment risk, and agriculture vulnerability
Resources	Resources, allocation, funds, time, staff capacity, policies, and who pays for adaptation

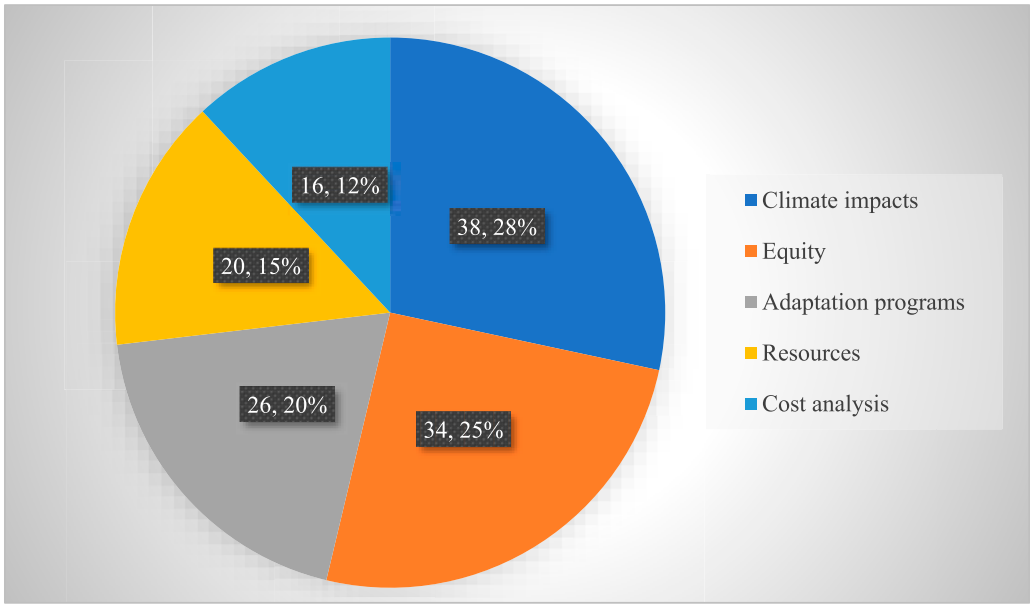

FIGURE 1
What kinds of decisions or issues do you face in your work related to climate change?

the sticky notes to account for their views so that other researchers and readers could potentially consider our findings and their use within their unique study and/or programs on climate adaptation. We also generated a summary of a word cloud using Microsoft PowerPoint to display the most predominant themes. In the discussions, we shared our insights into the findings, making connections between questions and their emergent themes within and amongst the cases. We also theorized with literature across different schools of thought participating in climate adaptation research fostering climate resilience in communities and provided recommendations on best practices around advancing the use of decision support while advising growers in adaptation efforts.

3 Results

3.1 Q1: What kinds of decisions or issues do you face in your work related to climate change?

Five major themes emerged from the responses with the majority of the codes aligning with decisions on climate impacts and equity. The other themes included adaptation programs, adaptation resources and cost analysis. Table 2 provides examples of codes aligned by themes and the estimated frequencies and percentages are provided in Figure 1.

In the equity theme, verbatims illustrate the lived experiences of stakeholders related to the kind of decisions they make or issues they face relating to climate. A participant wrote that they face issues on who is informed, involved and leading the [adaptation] projects, [they] added, breaking down barriers of mistrust and building meaningful relationships. Another participant wrote about how to effectively work together with multiple competing interests and do it fast when projects are complex and multi-jurisdictional. Those decisions or issues participants raised relate to equitably engaging with communities to get everyone on the decision-making table, facilitating and creating public buy-in to climate adaptation practices.

On adaptation programs, a participant wrote a decision they make relates to getting people (stakeholders) to understand the co-benefits of adaptation and gave an example that a community garden is good for food security, public health, biodiversity, urban cooling. Another participant added urban cooling and

wrote that [they] make decisions on what kind of trees would the public want? What [information] do they need before getting a tree? What is important for [household] when selecting a tree? Similarly, another participant wrote that at the city level, [they make decisions on] types of trees to plant for urban heat mitigation. These decisions reflect a desire to develop adaptation programs that are community-oriented to ease their implementation and also programs that have multiple benefits in climate adaptation, food systems, and urban development. On a broader perspective, one participant wrote a decision they make relates to what programs and information to deliver to households and organizations to implement to reduce [greenhouse gas] and adapt to changing climate with cost and added that the best outcome [is] for whole community as well as vulnerable. In preparation for the future, a participant wrote a decision [they] make decisions relates to assessing future crop locations with clearly illustrated uncertainty. These programs resonate with community engagement in creating community-driven adaptation practices.

In the climate impacts theme, one participant wrote, policy implementation–inclusive to the needs of communities who are historically at the foreface of the effects of climate change and added communities facing climate change related issues–heat, flooding. Another participant wrote heated cities and also added mental health people/violence. While another wrote species decline due to a warmer climate, changes in hydrology and changes in migration patterns. These impacts presented are both direct and indirect that affect agricultural productivity, species diversity, and human health, requiring the creation of effective adaptation practices to lessen their impact on the population and nature.

In the cost analysis theme, one wrote, as a state agency tasked with highway system, climate change will impact our infrastructure in various ways and many decisions must be made given [sea level rise] uncertainty and investment risk. Another participant wrote about how to make large cost decisions given uncertainty of projections. While another participant wrote, people and decision makers always ask for the low-hanging fruit in climate plans and added, cost [versus] benefit of it is usually thought of as [greenhouse gas] reduction but would be good to show co-benefits. The issues participants provided reflect the need for cost-benefit analysis of various adaptation pathways (including comparison of inaction) as one participant stressed it, that it can help stakeholders, agencies, and institutions make informed decisions while understanding the monetary and non-monetary benefits and the associated costs.

Relatedly, in the adaptation resources theme, one participant wrote a decision [they] make relating to who/when/how to engage the community and added, prioritizing climate action implementation in the context of limited resources and addressing multi-benefit potential in climate projects. Another participant wrote prioritizing resources for communities who have greatest vulnerability/need while another wrote how much to adopt now versus later? and added, who pays? The main codes that are illuminated relate to community engagement and prioritization of resources, which are among the greatest multipliers of the success of climate adaptation interventions. Engaging and involving communities in planning adaptation programs can reduce the cost of implementation and monitoring since projects become community-driven and communities as the primary beneficiaries of adaptation programs at a large scale.

3.2 Q2a). What information sources do you currently turn to, to help you make these decisions?

The major themes that emerged from this question were community and tribal knowledge, environment health tools, Cal-Adapt, reports and guides, research studies, and Health Places Index tool. Table 3 provides examples of the major information sources and tools, and Figure 2 depicts the frequencies and percentages associated with these all the information sources and data tools presented by the participants.

3.3 Q2b.) Where are the gaps or shortfalls in those information sources?

In this question, six themes emerged with the majority of the codes aligned with issues to do with limited translation and data update. The other themes included limited accessibility, data weight, resources, and low community participation. Examples of codes aligned by themes are provided in Table 4 and their estimated frequency of occurrence and percentages are provided in Figure 3.

Limited data translation was the major issue raised. A participant wrote that they use CIMIS [California Irrigation Management Information System] and added that [they] are looking for interpretations like those found in PRISM [Parameter-elevation Regressions on Independent Slopes Model] data. Another participant wrote CalEnviro is often applied incorrectly and added that people think pollution burden = climate burden. The experiences provided by the participants point to the need to improve and provide additional translation of the climatic data to support making the right use and interpretation of the climate model output for their unique farm operations. Furthermore, another participant narrated that sources are a collision of quantitative data and qualitative (here is what I am seeing in real life) and added that the gap is how to weigh data and decision approaches. Another participant was concerned about applicability and ease of use to everyday agricultural production. Related to lived experiences, a participant needed to see real information on successful communities managing growth differently and getting good results after practicing various adaptation strategies.

In the data updates theme, a participant wrote most recent data is often not available and added, so are always working with outdated data which makes it hard. Another participant wrote missing data and also added, how universal data is reported. These assertions point to the need for climate data managers and model developers to be alerted to continuously check the functionality of their websites. Relatedly, another participant wrote we need a real time data source/tool that brings in many factors for investment decisions pointing to the need to update and develop live climate models and tools that are interactive in real-time.

In the data access theme, a participant wrote, lack of governing body on data sources and another wrote no good data sharing portal in project specific data. These statements point to the availability of data that is inaccessible to the users. A related limitation was data weight, where a participant wrote too many tools, and another also

TABLE 3 Climate adaptation decision support information sources and tools.

Theme	Examples of codes
Community	Lived experiences, community knowledge, ground truthing, participatory approach, community concerns and needs, stakeholders, tribal knowledge
Cal-Adapt	California adaptation website
Reports	Climate assessment reports, adaptation planning guides, utility plans, and state/region/county/city plans
Environmental	CalEnviroScreen, Environmental Protection Agency, Justice40 Tool, Environmental Justice Screen 2.0, and Climate Change and Health Vulnerability Indicators for California
Studies	Science, case studies, research, literature
HPI	Health Places Index (HPI)
Coastal tools	Sea level rise modeling tool, Ocean Protection Council (OPC), Coastal Storm Modeling System (CoSMoS)/Our Coast Our Future (OCOF)

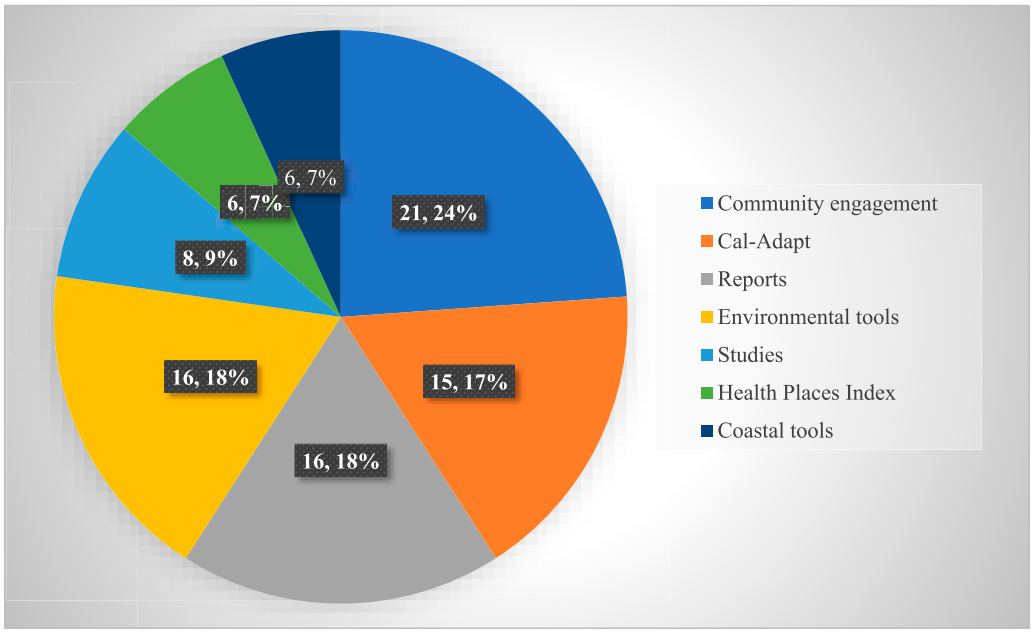

FIGURE 2
Climate adaptation decision support information sources and tools.

TABLE 4 Gaps or shortfalls in climate decision support information sources and tools.

Theme	Examples of codes
Limited translation	Translation, scalability, granulability, approaches
Data updates	Updates, current data, missing data, limited data, lack of data, local data
Limited accessibility	Data share, access, intergovernmental
Data weight	Data weight, heavy
Low community participation	Community, community-based organizations, lived experiences
Resources	Resources, funding, political

wrote, overwhelming amount of tools that are out there and added by asking a question, which one to use? One member advocated for data systems that cross boundaries, so you don't have to go to 10 sources to get all you need at community level as one way to overcome the overwhelming amount to data tools. Another shortfall was limited community participation, where one participant wrote

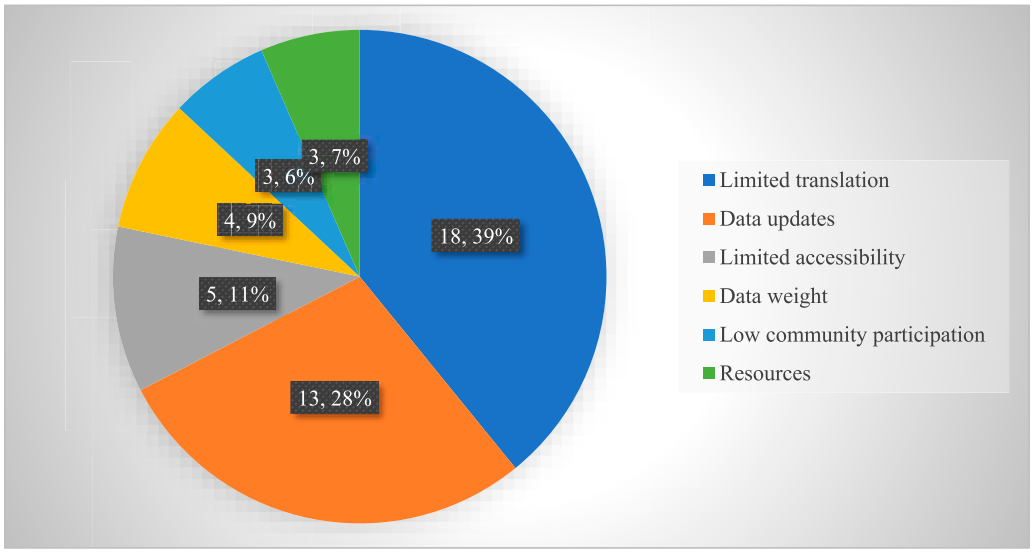

FIGURE 3
Gaps or shortfalls in the climate decision support information sources and tools.

TABLE 5 Strategies on how information tools can be more relevant and accessible to stakeholders.

Theme	Examples of codes
Community engagement	Case studies, engagement, community, groups, data users, partnerships, ask questions
Visualization	Visuals, video overviews, visualize, story maps, dashboards, graphics, 3D
Translation	Scalability, county scale data, snippets, actionable, multiple languages, usable, simplify
Dissemination	Disseminate, publicize, data sharing, communicate
Training	Training, education, extension
Update tools	Updating, more online tools, diversity of tools

about lack of lived experience/community inputs and needs. Community participation by harnessing their lived experience with tools and understanding how to make connections to solutions can influence their adaptation. Another major shortfall raised was resources which was reflected in statements related to limited funding.

3.4 Q3. How could information tools be more relevant and accessible to you and the groups you serve?

In this question, six themes emerged with the majority of the codes aligned with data visualization and dissemination. The other themes included translation, community engagement, updating tools and training. Table 5 provides examples of codes aligned by themes and their estimated frequencies and percentages are provided in Figure 4.

In the visualization theme, one participant wrote visual and video overviews (shorts) and also added ability to visualize local conditions and projections (Xeroltome, Sea Level Rise Viewer). Another participant wrote that decision support tools should be easy to use with great graphics. Related to visualization was the translation theme. In this theme, one participant wrote, make technical reports non-technical/data visualization tools and also added that relevance can be informed by the community. Another participant advised that engaging is more relevant to groups and added that tools should be easily accessible, and easily usable. The same participant went further to emphasize that tools should be local, very specific to local, easy to interpret by non-scientists. The translation reflects the importance of considering the end user of climate models, data, and tools made by climate scientists for non-scientific audiences, and engagements with the community can influence the public buy-in to climate science work.

The dissemination theme emphasizes improving accessibility to decision support tools. A participant wrote publicize success stories and also added that tool websites could include case studies of how groups used it to get funding/make change. This quote highlights the value of stories that vividly communicate lived experiences to inspire, change perceptions, and foster public buy-in to engage in climate adaptation work. Another theme to improving the relevance

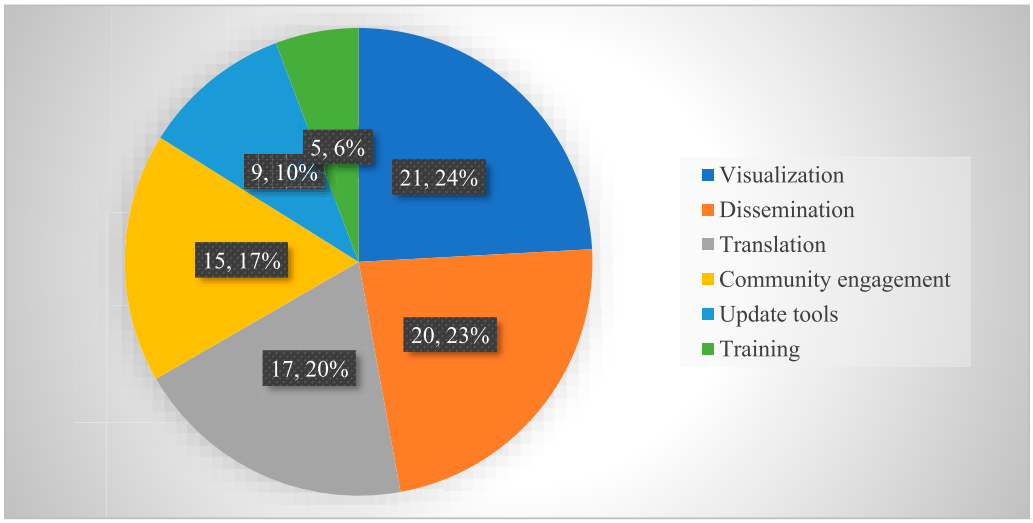

FIGURE 4
Strategies on how climate adaptation information tools can be more relevant and accessible to stakeholders.

of climate decision tools was updating tools as a participant put it wildfire data, need updating and scalability, and another participant wrote more tools, while another wrote diversity of tools. Updating tools helps the users to access current information from climate projections, especially for short-term where urgent actions are needed like frost in high-value specialty crops. The diversity of tools helps support the needs of growers in their unique commodities.

In the community engagement theme, participants felt that climate decision support providers should have broader criteria for identifying 'disadvantaged' communities BUT inform with community qualitative input data. Another participant wrote that people go to the simple words and advised that climate educators should ask for feedback from those communities–how would you like to be informed? Given the importance of communication across differences, another participant also advised educators to use multiple languages and use social media, and added, make tools represent realities communities see/feel. These verbatims illustrate the importance of tapping into the lived experiences of stakeholders from their communities who are at the forefront of experiencing the impact of climate change and to whom the climate decision support tools are made for their use to enhance their climate resilience.

Related to the training theme, participants felt that extension education and training of stakeholders will improve the usability of the climate decision support tools. One participant wrote teach more leaders of organizations to expect and use tools in their decision-making and also added that build tools from the bottom up. These responses reflect a need to coax leaders and policymakers into understanding the importance of climate decision-support tools in climate resilience programs that can also influence climate policy formulation in their programs. Another participant further added and emphasized that, provide training and be very clear on the narrow approach or utility of the new tool, and other existing tools [on] when and how to use which tool.

3.5 Q4. What can researchers do to help improve climate decision support?

In this question, five major themes emerged with the majority of the codes aligned with community engagement and data translation. The other themes included dissemination, training, and cost analysis. Table 6 provides examples of codes aligned by and Figure 5 illustrates the estimated frequencies and percentages by theme.

In the community engagement theme, participants advised researchers to proactively engage with communities in the co-creation of these tools and guides through research. One participant wrote research needs to be in the community, not just outreach ... and emphasized, make connections with the people around you and all the connections and industries they represent. Another participant added, better connection between the researcher and the public sector that needs certain questions answered or data needs for their agency/user. Engaging the community helps to move towards equity in climate work as one participant advised that identify important decision points at all levels and make sure data addresses those decision points, and added, help deal with barriers, gaps, policymakers, organizational leaders, households, individuals. Another participant wrote interface with communities better, especially vulnerable ones and another emphasized avoid biases, have an equity indicator, a move towards humanizing the data as one participant wrote. Similarly, more social science data, research that includes human impact resonated as one of the statements in community engagement.

Participants also feel researchers can help through translation of climate data. One participant wrote make tools as simple as possible and illustrated a scenario like what will happen if I plant "X" crop in this location in year "Y"? This scenario matches one of the responses to our question one that asked, what decision do you make relating to climate where one participant wrote, assessing future crop locations with clearly illustrated uncertainty. Continuing with the translation theme, another participant wrote research and added,

TABLE 6 How researchers can help improve climate decision support.

Theme	Examples of codes
Community engagement	Collaboration, community, engagement, research, outreach, connections, local areas, equity, environmental justice
Dissemination	Disseminate, accessible, communicate
Training	Training
Translation	Localize, translate, granular
Cost analysis	Cost-benefit-analysis

develop interpretation of the tools/data for agricultural producers to use in making decisions to adjust to climate change. Relatedly, participants feel researchers can help through training. In this theme, one participant emphasized continue to do training with public/private/[community-based organization] sector on tools beyond the initial roll out. Related to training was the dissemination theme and one of the participants wrote that disseminate your data and findings in ways that are accessible for; local practitioners, lay public, and added that work with local staff to set research agenda. These verbatims call on climate researchers to maintain the land-grant ethos that emphasizes research and discovery and relays the findings to the communities where the research was conducted to influence change and showcase the public value of their collaborative work.

In the cost analysis theme, participants feel researchers can go after the 'under the radar' wins and provided an example, like modeling where culverts should be upsized to save roads in the long term, potentially a bigger [Return on Investment] than [Sea Level Rise] adaptation. Another participant emphasized, include tools that account for the cost of NOT doing adaptation or not doing it fast enough. These verbatim reflect some of the decisions participants make relating to climate, for instance, one participant wrote a decision [they] make is on cost-benefit analysis of various adaptation pathways (including a comparison of inaction). However, one participant raised one of the issues [they] face related to when do we adapt and added what are our tipping points? all of which affect the timing of adaptation.

4 Discussion

Overall, three key themes summarize this investigation including community engagement and equity, data translations and visualization, and improving data accessibility through dissemination and training (see Figure 6). These themes bridge the gaps in decision support, define how decision support can be relevant, and also elaborate on what researchers can do to help advance decision support in advising producers on adaptation strategies.

4.1 Community engagement and equity in climate adaptation

Some of the climate adaptation decisions that stakeholders provided in this investigation revolve around policy implementation–inclusive to the needs of communities who are historically at the fore face of the effects of climate and weather variability. Adaptation programs that have embraced community engagement and promoting equity involving grassroots stakeholders have had successful efforts. For instance, enhancing urban ecosystems through planting trees has had implications for reducing urban heat and mental health, consequently reducing climate stressors in California (Hartin and Bennaton, 2023).

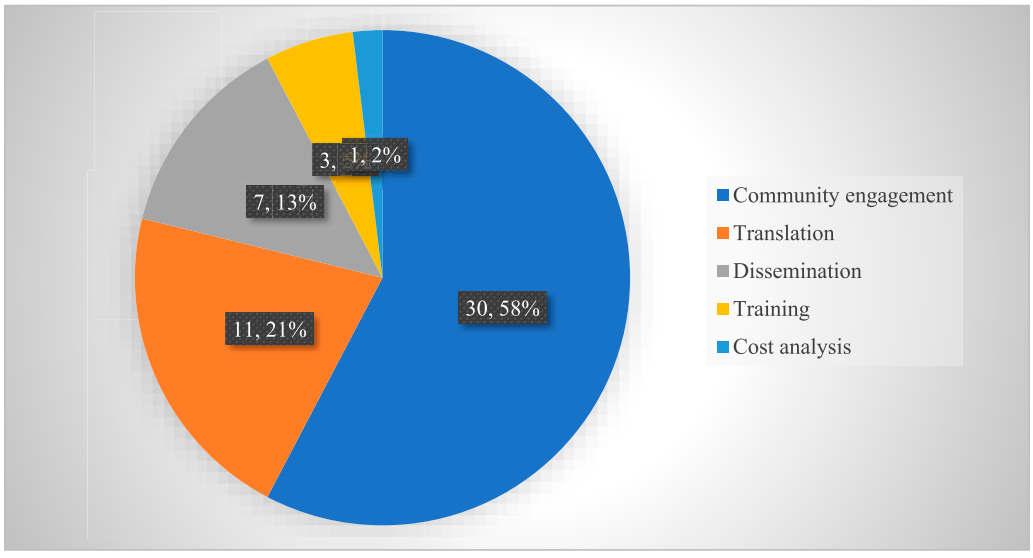

FIGURE 5
How researchers can help improve climate decision support.

FIGURE 6
Key themes of climate adaptation decision support.

Relatedly, community engagement and tribal knowledge were the most used decision-support information sources. Engaging a network of community stakeholders helps to uncover the climate risk management practices they currently use, what tools and resources would assist them in making strategic decisions, and what types of extension education activities would help them in choosing and implementing adaptation practices and where to find necessary resources (Ikendi et al., 2024a; Jasperse and Pairis, 2020a; Kanter et al., 2021; Pinzón et al., 2025). Similarly, tribal knowledge is beneficial in understanding the sacred norms that impact specific tribal adaptation efforts (Martinez et al., 2024; Schramm et al., 2020). The Pala Band of Mission Indians in San Diego, for instance, are among the Climate-Ready Tribes Initiatives created by the Centers for Disease Control and Prevention and the National Indian Health Board (Schramm et al., 2020). The Pala have customized their adaptation strategies through tribal-led needs assessments and have created adaptation programs tailored to their local language and cultural norms. Relatedly, the Hmong in the San Joaquin Valley have also been engaged in adaptation needs assessments to understand their unique experiences and practices through their local language (Taku-Forchu et al., 2024). The inclusion of relevant local languages is one way to create interrelated biodiversity in adaptation and sustainable agricultural efforts (Ikendi, 2023; Maffi, 2018). Community engagements in adaptation needs assessments have been instrumental in developing educational programs that are receptive to community needs.

Similarly, community engagement resonated with a gap in the adaptation decision support reflected in quotes like *lack of lived experience/community inputs and needs*. Participants advised that decision support can be more relevant if climate scientists and educators involve communities by *asking for feedback from those communities – how would you like to be informed?* It was further emphasized that *research needs to be in the community, . . . make connections with the people . . . and industries they represent*. These assertions depict the essential role of starting from where people are in delivering adaptation programs including decision support tools. Several programs in California that have embraced community involvement in needs assessment have seen improvements in adaptation with impactful outcomes. For instance, cooling urban heat islands using trees (Hartin and Bennaton, 2023); advancing adaptation knowledge through extension workshops for advisers (Ikendi et al., 2025a; Parker et al., 2023); adaptation curricula based on tribal knowledge (Schramm et al., 2020); enhancing urban agriculture for food and nutrition security (Surls et al., 2023). Community engagement through participatory needs assessment is one of the strategies to ensure equity by harnessing input from members including minorities and tribal communities. This strategy is in line with the California *Farmer Equity Act* (CDFA, 2020), and the fifth California Climate Assessment report (Governor's Office of Planning and Research, 2024) and generally a move toward "*humanizing*" adaptation data as asserted by one of the participants while emphasizing the need for equity and justice indicators in adaptation decision support.

4.2 Translation and visualization of adaptation data and tools

Adaptation data translation and visualization were outstanding themes relating to addressing the gaps in decision support, how can decision support be relevant, and what researchers can do to help advance decision support. One participant provided an example of where [they] use CIMIS [California Irrigation Management Information System] datasets and tools but are looking for interpretations like those of PRISM [Parameter-elevation Regressions on Independent Slopes Model] datasets. The CIMIS dataset and tools support stakeholders using irrigation water for efficient planning to minimize costs (California Department of Water Resources, 2016) and implementation of the Sustainable Groundwater Management Act in regulating water quantity (Söller et al., 2025). On the other hand, PRISM datasets are developed from climate observations to support projections of

climate and weather patterns over time and spatial scales (Northwest Alliance for Computational Science and Engineering, 2024). The CalAgroClimate (Pathak et al., 2023) have developed monitoring tools including frost and heat using high-resolution PRISM datasets within 800 meters and 4-km grids where farmers can estimate frost or heat risk within 7 days and in their locale to take precautionary measures to reduce their impacts. These tools developed by the team have good visualization and translation which was raised as the most important aspect of how decision support can be more relevant to users.

Also, data translation and visualization are reflected in adaptation websites identified during the investigation including California adaptation (Cal-Adapt), Environment tools (e.g., Cal Enviro), Health Places Index, and Coastal Storm Modeling System. Specifically, Cal-Adapt provides stakeholders with climate tools that project temperature, precipitation, sea level rise, wildfire, and snowpack at different spatial scales; time frames, and at different emission scenarios (Cal-Adapt, 2024). Scientists have used Cal-Adapt tools to transform the forecast into more practical forms for infrastructure planning in agriculture and the environment (Pathak et al., 2018; Pierce et al., 2018) and research in urban development (Deas, 2015). The need for locally tailored tools improves data utilization, with especially well-designed tools. In the design of a Community Adaptation Viewer, a prototype web-based spatial decision support system for climate adaptation planning (Lieske, 2015), users valued visualizations that centered on landmarks known to them, such as their neighborhoods and districts. Such aspects reinforce the usefulness of interactive web-based mapping tools to the users. In the Community Adaptation Viewer, users can 'pan and zoom' to find their parcels or districts. A design similar to CalAgroClimate where users can identify their zone using zip codes when assessing the risk of frost and heat, providing real-time data in a locale to facilitate timely mitigation planning (Pathak et al., 2023).

Reports and guides were also highly used as adaptation decision-support information sources with well-translated and visualized climate data. Most cited reports in this investigation were climate assessment reports, planning guides, and utility reports all of which offer stakeholders a broader understanding of climate and weather impacts, adaptation strategies, and their progress for the case of time series or periodical reports. Some reports are developed out the climate models using the current and projected climate data and original research. For instance, the fifth climate assessment report for California is expected to have smaller spatial data, embedded with new climate data, emphasizing regional and tribal knowledge in the design of adaptation strategies, among others (Governor's Office of Planning and Research, 2024). Also, some reports generally depict annual production and adaptation strategies (e.g., CDFA, 2023a); while others focus on addressing adaptation indicators like equity (e.g., CDFA, 2020), senate bills on adaptation (e.g., Gavin Newsom, 2023) and policy briefs (e.g., Escriva-Bou et al., 2023; Harder et al., 2025; Sommer et al., 2024). Others are agency-specific reports addressing their vision and strategies, for instance, clean air (California Air Resources Board, 2020; California Air Resources Board, 2024); water resources (California Water Watch, 2024; Reich et al., 2018); energy (California Energy Commission, 2023). Whereas other reports are programmatic addressing adaptation strategies and resources, for instance, soil health (CDFA, 2023b). Also, others are built as adaptation extension education materials, offering a breadth of translation, visualization, and interpretation of climate data for action planning and advising by extension educators (e.g., Jasperse and Pairis, 2020b; Parker et al., 2023).

4.3 Adaptation data accessibility, dissemination, and training

Accessibility was among the limitations of adaptation decision support especially for data that involves payments (i.e., the cost depends on the type of data needed like PRISM [Northwest Alliance for Computational Science and Engineering, 2024]). Dissemination and training through regional workshops with Extension technical service providers can be one of the strategies to improve data access, translation, and use of data tools (Ikendi et al., 2025a). For instance, while PRISM data has some associated costs, some agencies have secured funds and procured some datasets that have been used to create different monitoring tools like frost, heat, and pests of which their use has been trained to farmers and technical service providers alongside other adaptation strategies (Pathak et al., 2023). Further, several approaches like creating climate resource workbooks with in-built adaptation scenarios have been devised by climate scientists and educators, for instance, the USDA California climate hub and UC Agriculture and Natural Resources (Parker et al., 2023). Working with local staff and stakeholders has been one of the ways to create the research agenda, adaptation strategies, and steering community education programs in climate adaptation, water conservation on varied landscapes (Hartin et al., 2019), urban ecosystem conservation (Hartin and Bennaton, 2023), including tribal communities (Martinez et al., 2024; Schramm et al., 2020).

5 Conclusions, implications and recommendations

This investigation with the Extension technical service providers uncovered their lived experiences around decision support for climate adaptation. Overall, three key themes summarize this investigation including community engagement and equity, data translations and visualization, and improving data accessibility through dissemination and training. These themes bridge the gaps in decision support, define how decision support can be relevant, and also elaborate on what researchers can do to help advance decision support in climate adaptation efforts in agriculture and natural resources. All the themes and verbatims call on climate researchers to maintain the land-grant ethos that emphasizes research and discovery and relays the findings back to the communities where the research was conducted to influence change towards adaptation and showcase the public value of their collaborative work. This strategy is important since the investigation found that all those decisions or issues participants raised relate to equitably engaging with communities to get everyone on the decision-making table, facilitating and creating public buy-in to climate work. Engage the Extension technical service providers in extension education programs on adaptation decision support and equip them with the necessary tools like adaptation curricula and

resources that will help in their adaptation advising (Ikendi et al., 2025a; Parker et al., 2023).

Looking at the dominant patterns that emerged, the investigation found it striking that many of the stakeholders reported a decision space which cannot really be answered by scientific data or models (e.g., who is doing what, where can we find funding, how do we build trust). This finding highlights the importance of taking a broad perspective on what constitutes decision support and developing collaborations between researchers (i.e., who are good with data and models), agencies, and community-based organizations, and supporting policies to break down the silos between those different organizations. The investigation also identified a lot of useful information for adaptation tool builders, starting with the fact that most commonly used resources for adaptation are not apps and data, but rather networks of trusted people, communities of practice, and reports. What these resources have in common is that they help people learn, build connections, bridge the trust gap, and develop a toolbox of adaptation strategies. This aspect is opposed to merely informing a well-defined decision, which is what researchers like to do. Another body of scholarship this pattern speaks to is how extension has evolved from a top-down model where experts provided the information, to the modern day where universities and experts are but one of many resources people turn to for information, a model referred to as Extension 3.0 (Lubell et al., 2014).

The long list of gaps in decision support tools, and the verbatims about their relevance (or lack thereof), is humbling but not really surprising. What is more perplexing is that these are the same gaps that have been reported for years as discussed in the background section. These gaps suggests that there is something deeper at work, which might include institutional incentives, research time frames, funding, and maybe the epistemological assumptions of researchers that are reductionist and ignore important criteria as externalities; Pearman and Cravens (2022) explored this by studying tool developers rather than tool users. And underpinning the reproduction of these limitations generation after generation are the directions of accountability. These aspects further supports the need for collaboration between public agencies (which are more accountable to the stakeholders) and research organizations like Cooperative Extension which have accountability (through the Cooperative funding model) and reward impact in addition to scholarship. The need to teach organizational leaders was also retaliated by some of the members. A well-designed decision support system can help in these efforts by offering special 'Executive Summary' type content for busy administrators. Other special dissemination materials could be targeted at teachers at school-age children, for instance, through special videography or public presentations. There are efforts targeting community college and university students in learning about climate science communication as future agriculture leaders and advisors who can support growers with science-based information to facilitate adaptation (Ikendi et al., 2025b; Dooley and Grady, 2020; Leal Filho et al., 2021; Reimers, 2020; Rousell & Cutter-Mackenzie-Knowles, 2020; Stein, 2024).

The findings of study also highlights an understanding why people choose not to use a decision support tool, which very few studies try to look at because it is a difficult question, and the results can be uncomfortable (Cravens, 2018). The study also identified connections between the calls for better visualization and translation of data and models to actionable information, both of which might be able to explain the inherent uncertainty and complexity in weather, climate, and production systems. There were also some tensions between the themes identified such as a desire for everything to be simple and user friendly, but also include lots of local information, informing specific management and planning needs (which themselves are complex), address additional uncertainties in production, markets, regulations and be free to use. A key advantage of decision support systems is that they can act as information hubs, where users can access the best practice documents, engaging short video overviews, news, and announcements about future workshops and events, and interviews with stakeholders, among other items. Users can opt to use any information that suits their situation.

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 humans were approved by University of California Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin because information obtained was only meant for research publication reasons and not for any other purposes.

Author contributions

SI: Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing. AL: Conceptualization, Data curation, Investigation, Project administration, Resources, Supervision, Writing – original draft, Writing – review and editing. TP: Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – original draft, Writing – review and editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The study was funded by the U.S. Department of Agriculture–National Institute of Food and Agriculture, Grant Number: 2022-68017-36358.

Acknowledgments

The authors would like to thank Janet Hartin, Romain Maendly, Michael Wolff, and Bob Klein for their presentations and support in

moderating the discussions during the breakout sessions where the data for this article was obtained.

Conflict of interest

The 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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1605176/full#supplementary-material

References

Adebiyi, A. A., Kibria, M. M., Abatzoglou, J. T., Ginoux, P., Pandey, S., Heaney, A., et al. (2025). Fallowed agricultural lands dominate anthropogenic dust sources in California. *Comm Earth and Env* 6 (1), 324. doi:10.1038/s43247-025-02306-0

Cal-Adapt. (2024). *Climate tools*. California Energy Commission: Sacramento California, United States. Available online at: https://cal-adapt.org/tools/(Accessed December 10, 2024).

California Air Resources Board (2020). *California air resources board vision and roadmap: clean air for all californians*. Sacramento: California, United States. Available online at: https://ww2.arb.ca.gov/sites/default/files/2021-01/CARB_vision_roadmap_0121.pdf.

California Air Resources Board (2024). *Current California GHG emission inventory data: 2000-2020 GHG inventory*. Sacramento: California, United States. Available online at: https://ww2.arb.ca.gov/ghg-inventory-data.

California Cattlemen's Association (2023). Ranching in California. Available online at: https://calcattlemen.org/ranching-in-california/([Last accessed December 20, 2024).

California Department of Food and Agriculture (2023a). *California agricultural statistics review 2022-2023*. Sacramento: California, United States. Available online at: https://www.cdfa.ca.gov/Statistics/PDFs/2022-2023_california_agricultural_statistics_review.pdf.

California Department of Food and Agriculture (2023b). *Soil biodiversity in California agriculture: framework and indicators for soil health assessment*. Sacramento: California, United States. Available online at: https://www.cdfa.ca.gov/oefi/biodiversity/docs/Soil_Biodiversity_California_Ag_July_2023.pdf.

California Department of Food and Agriculture (CDFA) (2020). "2020 report to the California legislature on the farmer equity act,". Sacramento California. Available online at: https://www.cdfa.ca.gov/farmerresources/pdfs/2020FarmerEquityReport.pdf.

California Department of Water Resources (2016). "Drought and water year 2016: hot and dry conditions continue,". Sacramento California. Available online at: https://cwc.ca.gov/-/media/DWR-Website/Web-Pages/Water-Basics/Drought/Files/Resources/Water-Year-2016-Drought-Conditions-Continues.pdf.

California Energy Commission (2023). *Renewable energy for agriculture program*. Sacramento: California, United States. Available online at: https://www.energy.ca.gov/programs-and-topics/programs/renewable-energy-agriculture-program.

California Water Watch (2024). *Water year 2022-2023 yearly summary*. California Department of Water Resources: Sacramento, CA. Available online at: https://cww.water.ca.gov/yearly-summary (Accessed on December 2, 2024).

Cravens, A. E. (2018). How and why upper colorado river basin land, water, and fire managers choose to use drought tools (or not): U.S. geological survey open-file report 2018–1173. doi:10.3133/ofr20181173

Creswell, J. W., and Poth, C. N. (2018). *Qualitative inquiry and research design: choosing among five approaches*. Sage Thousand Oaks, CA.

Deas, M. S. (2015). Cal-Adapt and the usability of climate adaptation tools [Master's Thesis]. Massachusetts Institute of Technology, Cambridge, Massachusetts. Available online at: https://dspace.mit.edu/handle/1721.1/99075.

Dooley, K. E., and Grady, R. T. (2020). Agricultural education and extension curriculum innovation: the nexus of climate change, food security, and community resilience. *Jour Agric Educ Ext* 26 (1), 1–3. doi:10.1080/1389224X.2019.1703507

Escriva-Bou, A., Hanak, E., Cole, S., and Medellín-Azuara, J. (2023). *The future of agriculture in the san joaquin valley: policy brief*. San Francisco: California, United States: Public Policy Institute of California. Available online at: https://www.ppic.org/wp-content/uploads/policy-brief-the-future-of-agriculture-in-the-san-joaquin-valley.pdf.

Gavin Newsom, G. (2023). "Building the electricity grid of the future: california's clean energy transition plan,". Sacramento, CA. Available online at: https://www.gov.ca.gov/wp-content/uploads/2023/05/CAEnergyTransitionPlan.pdf.

Governor's Office of Planning and Research (2024). Climate assessment, science, and research: california's fifth climate change assessment, research priorities, and tools. Available online at: https://opr.ca.gov/climate/icarp/climate-assessment/#fifth-assessment (Accessed on December 12, 2024).

Grantham, T., Kearns, F., Kocher, S., Roche, L., and Pathak, T. (2017). Building climate change resilience in California through UC cooperative extension. *Cal. Agric.* 71 (4), 197–200. doi:10.3733/ca.2017a0045

Harder, H., Gray, B., Grenier, L., Hanak, E., Sencan, G., and Sommer, T. (2025). *Implementing climate-smart conservation: law and institutions*. San Francisco: California, United States: Public Policy Institute of California. Available online at: https://www.ppic.org/publication/implementing-climate-smart-conservation/.

Hartin, J., and Bennaton, R. (2023). *Benefits of plants to humans and urban ecosystems*. University of California, Division of Agriculture and Natural Resources Publication, 8726. doi:10.3733/ucanr.8726

Hartin, J., Oki, L. R., Fujino, D. W., Reid, K., Ingels, C. A., Haver, D. L., et al. (2019). UC ANR research and education influences landscape water conservation and public policy. *Calif. Agric.* 73 (1), 25–32. doi:10.3733/ca.2018a0041

Ikendi, S. (2023). Ecological conservation, biodiversity, and agricultural education as integrated approaches for envisioning the future of sustainable agriculture in North America. *Int. J. Sus Dev. World Ecol.* 30 (5), 152–163. doi:10.1080/13504509.2022.2127032

Ikendi, S., Koundinya, V., Taku-Forchu, N. C., Pinzón, N. J., Roche, L. M., Ostoja, S., et al. (2024b). "Current state, and future potential of using climate decision support tools for agricultural decision-making in California poster presentation," in Association for International Agricultural and Extension Education Annual Conference, Orlando, Florida, 631–636. Available online at: https://www.researchgate.net/publication/384246356.

Ikendi, S., Moreland, K., Parker, L., Ostoja, S., Koundinya, V., Pathak, T., et al. (2025a). "Enhancing the capacity of extension technical service providers to address climate and weather variability concerns in California (Oral presentation, pp. 297–299). in *Association for international agricultural and extension education annual conference.* (Inverness, Scotland) Available online at: https://www.researchgate.net/publication/392472811.

Ikendi, S., Pinzón, N., Koundinya, V., Taku-Forchu, N., Roche, L., Ostoja, S., et al. (2024a). Climate smart agriculture: assessing needs and perceptions of California's farmers. *Front. Sustain. Food Syst.* 8, 1395547. doi:10.3389/fsufs.2024.1395547

Ikendi, S., Rios, K. D., Jha, P. K., and Pathak, T. (2025b). "Developing the next generation of climate-ready workforce in California (poster presentation, pp. 101–104)" in American Association for Agricultural Education National Conference (Lubbock, TX): Available online at: https://www.researchgate.net/publication/391849719.

Jagannathan, K., Pathak, T. B., and Doll, D. (2023). Are long-term climate projections useful for on-farm adaptation decisions? *Front. Clim.* 4, 1005104. doi:10.3389/fclim.2022.1005104

Jasperse, L., and Pairis, A. (2020a). Climate change consortium for specialty crops: Southern California region. Sacramento, CA: California Department of Food and

Agriculture and Climate Science Alliance. Available online at: https://drive.google.com/file/d/1Or8aOFw7-BzLF85B0Mg-0CPOae9Dhcto/view (Accessed November 10, 2024).

Jasperse, L., and Pairis, A. (2020b). *Climate change impacts for specialty crops: summary guide*. Sacramento, CA: California Department of Food and Agriculture and Climate Science Alliance. Available online at: https://drive.google.com/file/d/1MwSYonfGJtWPn7zDj-v7MVesD0_9fcXn/view (Accessed November 10, 2024).

Jha, P. K., Zhang, N., Rijal, J. P., Parker, L. E., Ostoja, S., and Pathak, T. B. (2024). Climate change impacts on insect pests for high value specialty crops in California. *Sci. Total Environ.* 906, 167605. doi:10.1016/j.scitotenv.2023.167605

Johnson, D., Parker, L. E., Pathak, T. B., Crothers, L., and Ostoja, S. M. (2023). Technical assistance providers identify climate change adaptation practices and barriers to adoption among California agricultural producers. *Sustainability* 15, 5973. doi:10.3390/su15075973

Kanter, J., Clark, N., Lundy, M. E., Koundinya, V., Leinfelder-Miles, M., Long, R., et al. (2021). Top management challenges and concerns for agronomic crop production in California: identifying critical issues for extension through needs assessment. *Agron. J.* 113 (6), 5254–5270. doi:10.1002/agj2.20897

Leal Filho, W., Sima, M., Sharifi, A., Luetz, J. M., Salvia, A. L., Mifsud, M., et al. (2021). Handling climate change education at universities: an overview. *Env. Sci. Eur.* 33, 109. doi:10.1186/s12302-021-00552-5

Lewis, J., and Rudnick, J. (2019). The policy enabling environment for climate smart agriculture: a case study of California. *Front. Sustain Food Syst.* 3, 31. doi:10.3389/fsufs.2019.00031

Lieske, D. J. (2015). Coping with climate change: the role of spatial decision support tools in facilitating community adaptation. *Env Model and Softw.* 68, 98–109. doi:10.1016/j.envsoft.2015.02.005

Lincoln, Y. S., and Guba, E. G. (1985). *Naturalistic inquiry*. Sage: New Dheli, India.

Lu, J., Singh, A. S., Koundinya, V., Ranjan, P., Haigh, T., Getson, J. M., et al. (2021). Explaining the use of online agricultural decision support tools with weather or climate information in the midwestern United States. *J. Environ. Man.* 279, 111758. doi:10.1016/j.jenvman.2020.111758

Lubell, M., Niles, M., and Hoffman, M. (2014). Extension 3.0: managing agricultural knowledge systems in the network age. *Soc. and Nat. Resour.* 27 (10), 1089–1103. doi:10.1080/08941920.2014.933496

Maffi, L. (2018). "Biocultural diversity," in *The international encyclopedia of anthropology*. Editor H. Callan (New York (NY): John Wiley and Son), 1–14.

Martinez, D. J., Meadow, A. M., Manning, B. R. M., and Maldonado, J. (2024). Climate justice and climate adaptation in California: indigenous community climate adaptation leadership and opportunities for scientific collaboration. *Weather, Clim, Soc* 16 (3), 399–409. doi:10.1175/WCAS-D-23-0112.1

Munden-Dixon, K., Tate, K. W., Cutts, B. B., and Roche, L. M. (2018). An uncertain future: climate resilience of first-generation ranchers. *Rangel. J* 41 (3), 189–196. doi:10.1071/rj18023

Northwest Alliance for Computational Science and Engineering (2024). Climate data at NACSE. Available online at: https://www.nacse.org/prism/(Accessed December 1, 2024).

Parker, L. E., Johnson, D., Pathak, T. B., Wolff, M., Jameson, V., and Ostoja, S. M. (2023). *Adaptation resources workbook for California specialty crops. USDA California climate hub technical report CACH-2023-1*. Available online at: https://www.climatehubs.usda.gov/hubs/california/topic/adaptation-resources-workbook-california-specialty-crops.

Parker, L. E., McElrone, A. J., Ostoja, S. M., and Forrestel, E. J. (2020). Extreme heat effects on perennial crops and strategies for sustaining future production. *Plant Sci.* 295, 110397. doi:10.1016/j.plantsci.2019.110397

Parker, L. E., Zhang, N., Abatzoglou, J. T., Ostoja, S. M., and Pathak, T. B. (2022). Observed changes in agroclimate metrics relevant for specialty crop production in California. *Agron* 12, 205. doi:10.3390/agronomy12010205

Pathak, T. B., Maskey, M. L., Dahlberg, J. A., Kearns, F., Bali, K. M., and Zaccaria, D. (2018). Climate change trends and impacts on California agriculture: a detailed review. *Agron* 8, 25. doi:10.3390/agronomy8030025

Pathak, T. B., Ostoja, S., Jha, P. K., Parker, L., and Johnson, R. (2023). *CalAgroClimate. Org–web-based decision support system for managing agriculture under weather and climate risks*. San Francisco, California: United States: American Geographical Union. Available online at: https://calagroclimate.org/.

Pearman, O., and Cravens, A. E. (2022). Institutional barriers to actionable science: perspectives from decision support tool creators. *Environ. Sci. and Policy* 128, 317–325. doi:10.1016/j.envsci.2021.12.004

Pierce, D. W., Kalansky, J. F., Cayan, D. R., and Scripps Institution of Oceanography (2018). *Climate, drought, and sea level rise scenarios for the fourth California climate assessment*. California Energy Commission: Sacramento, CA. Available online at: https://www.energy.ca.gov/sites/default/files/2019-11/Projections_CCCA4-CEC-2018-006_ADA.pdf.

Pinzón, N., Galt, R., Roche, L., Schohr, T., Shobe, B., Koundinya, V., et al. (2025). Farming and ranching through wildfire: producers' critical role in fire risk management and emergency response. *Cal. Agric.* doi:10.3733/001c.128403

Ranjan, P., Duriancik, L. F., Moriasi, D. N., Carlson, D., and Prokopy, L. S. (2020). Understanding the use of decision support tools by conservation professionals and their education and training needs: an application of the reasoned action approach. *J. Soil Water Conserv.* 75 (3), 387–399. doi:10.2489/jswc.75.3.387

Reich, K. D., Berg, N., Walton, D. B., Schwartz, M., Sun, F., Huang, X., and Hall, A. (2018). Climate change in the Sierra Nevada: California's water future. University of California, Los Angeles, Center for ClimateScience: Los Angeles, CA. Available online at: https://www.ioes.ucla.edu/wp-content/uploads/UCLA-CCS-Climate-Change-Sierra-Nevada.pdf

Reimers, F. M. (2020). *Education and climate change: the role of universities* (Springer).

Roche, L. M. (2021). Grand challenges and transformative solutions for rangeland social-ecological systems–emphasizing the human dimensions. *Rangelands* 43 (4), 151–158. doi:10.1016/j.rala.2021.03.006

Roche, L. M., Schohr, T. K., Derner, J. D., Lubell, M. N., Cutts, B. B., Kachergis, E., et al. (2015). Sustaining working rangelands: insights from ranche r decision making. *Rangel. Ecol. and Mgt* 68 (5), 383–389. doi:10.1016/j.rama.2015.07.006

Rossman, G. B., and Rallis, S. F. (2017). *An introduction to qualitative research: learning in the field*. Sage: Thousand Oaks, CA.

Rousell, D., and Cutter-Mackenzie-Knowles, A. (2020). A systematic review of climate change education: giving children and young people a 'voice' and a 'hand' in redressing climate change. *Child. Geog* 18 (2), 191–208. doi:10.1080/14733285.2019.1614532

Saldaña, J. (2024). "An introduction to themeing the data," in *Expanding approaches to thematic analysis: creative engagements with qualitative data*. Editors J. R. Wolgemuth, K. W. Guyotte, and S. A. Shelton (Routledge: London, United Kingdom), 11–26.

Schramm, P. J., Al Janabi, A. L., Campbell, L. W., Donatuto, J. L., and Gaughen, S. C. (2020). How Indigenous communities are adapting to climate change: insights from the climate-ready tribes initiative. *Health Aff.* 39 (12), 2153–2159. doi:10.1377/hlthaff.2020.00997

Skendžić, S., Zovko, M., Živković, I. P., Lešić, V., and Lemić, D. (2021). The impact of climate change on agricultural insect pests. *Insects* 12 (5), 440. doi:10.3390/insects12050440

Söller, L., Foglia, L., and Harter, T. (2025). Groundwater models through stakeholders' eyes: evaluating benefits, challenges, and lessons for SGMA implementation. *Cal. Agric.* 79 (1), 19–27. doi:10.3733/001c.127420

Sommer, T., Mount, M., Gray, G., Grenier, L., Harder, J., and Sencan, G. (2024). *Climate-smart tools to protect California 's freshwater biodiversity*. San Francisco: California, United States: Public Policy Institute of California. Available online at: https://www.ppic.org/publication/climate-smart-tools-to-protect-californias-freshwater-biodiversity/.

Stein, S. (2024). Making space for critical climate education. *About Campus* 29 (5), 4–13. doi:10.1177/10864822241284622

Surls, R. A., Bennaton, R., Feenstra, G. W., Lobo, R. E., Pires, A. F., Sowerwine, J., et al. (2023). Urban agriculture in California: lessons learned from an urban farmer workshop series. *Calif. Agric.* 77 (2), 57–62. doi:10.3733/ca.2023a0010

Swain, D. L., Singh, D., Touma, D., and Diffenbaugh, N. S. (2020). Attributing extreme events to climate change: a new frontier in a warming world. *One Ear* 2 (6), 522–527. doi:10.1016/j.oneear.2020.05.011

Taku-Forchu, N., Ikendi, S., Koundinya, V., Dahlquist-Willard, R., Thaoxaochay, L., Vong, M., et al. (2024). Climate adaptation information needs of limited resource farmers in California. *Res. Square*. doi:10.21203/rs.3.rs-4676276/v1

United States Government Accountability Office (USGAO) (2014). *Climate change: usda's ongoing efforts can be enhanced with better metrics and more relevant information for farmers*. Washington DC: United States. Available online at: https://www.gao.gov/assets/gao-14-755.pdf.

Woodmansee, G., Macon, D., Schohr, T., and Roche, L. (2025). Building ranch resilience to drought: management capacity, planning, and adaptive learning during California's 2012-2016 drought. *Rangel. Ecol. Mgt* 98, 63–72. doi:10.1016/j.rama.2024.07.009

Zhang, N., Pathak, T. B., Parker, L. E., and Ostoja, S. M. (2021). Impacts of large-scale teleconnection indices on chill accumulation for specialty crops in California. *Sci. Total Environ.* 791, 148025. doi:10.1016/j.scitotenv.2021.148025