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Authors
Wong, Christiana
Moghimi, Ali

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Stakeholder mapping of precision weeding commercialization ecosystem in California

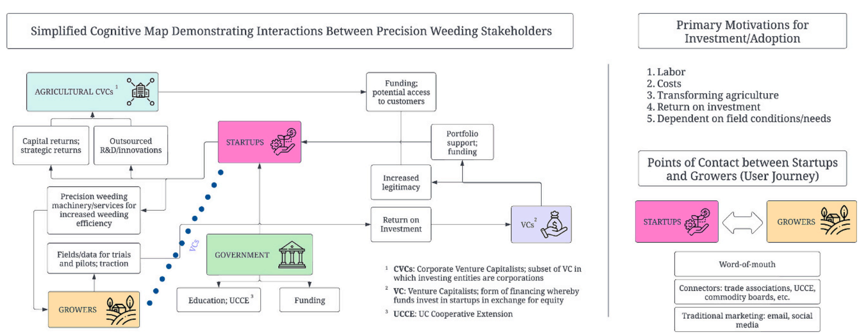
Christiana Wong [a], Ali Moghimi [b,*]

[a] Rausser College of Natural Resources, University of California, Berkeley, CA 94709, USA
[b] Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616, USA

HIGHLIGHTS

- Precision weeding is moving from research to market, helping growers address labor and environmental concerns.
- Study investigated the shared interests/concerns and dynamics between California growers, startups, and venture capitalists.
- Coded and created stakeholder maps to analyze 17 semi-structured interviews, distilling stakeholder dynamics.
- Shared interests: labor, cost reduction, transformative potential. Concerns: startup longevity, startup-grower relationships.
- Qualitative cognitive mapping can be applied to other emerging agtech technologies and ecosystems.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Precision weeding, a sector of agricultural technology in which drones and/or automated weeders use chemical, mechanical, or thermal means to eradicate weeds, has moved from academic research settings to commercialization. Because of labor shortage pressures, the push to gain competitive advantages, and the environmental impacts of excessive chemical inputs, many California growers have been interested in adopting precision weeding technologies in their operations.
OBJECTIVE: Using semi-structured qualitative interviews, this study investigated the viewpoints of three key stakeholder groups involved in the diffusion and adoption of precision weeding technologies: California growers, precision weeding startups, and agricultural technology venture capital firms. With the supplemental viewpoints of large agricultural firms and their corporate venture capital arms and government agencies, this study seeks to understand the compatible motivations between stakeholders, current collaborative models between stakeholders and their limitations, and the user journey for growers adopting precision weeding technology.
METHODS: We conducted 17 semi-structured qualitative interviews with diverse stakeholders in the precision weeding sector to gather textual data and gain high data saturation. Data collection balanced rigorous criteria for participant selection with adaptive interview questions to ensure depth and relevance. The analysis procedure

* Corresponding author.
E-mail addresses: christiana.w@berkeley.edu (C. Wong), amoghimi@ucdavis.edu (A. Moghimi).

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involved coding and thematic framework development, complemented by grounded theory for iterative data examination and stakeholder map creation for distilling cross-organizational insights and stakeholder dynamics.
RESULTS AND CONCLUSIONS: The results indicated that compatible motivations include addressing current labor issues, reducing costs, and the potential of precision weeding to transform agriculture. Less cited but still popular motivations included having more weeding options, meeting specific field needs, and environmental sustainability. The individual and stakeholder group cognitive maps demonstrated that concerns such as startup longevity, the high expenses of precision weeding machinery, and some startups lacking a direct connection to growers commonly limit the growers' adoption of precision weeding technologies.
SIGNIFICANCE: The procedure and cognitive mapping presented in this study can be applied to other emerging agtech technologies and ecosystems.

1. Introduction

In commercial agriculture, weeds threaten effective crop production by competing with agricultural crops for resources (e.g., light, water, and nutrients), depleting soil nutrients, and interfering with agricultural operations, such as harvesting. In addition, weeds may serve as hosts for pests and pathogens, disrupting crop production. The most common weed management strategy is the application of herbicides and pesticides. In 2017, over 400 types of pesticides were used in the United States, amounting to over one billion pounds (Acharya, 2020). Despite the prevalence of pesticides, weed management for specialty crops still faces significant issues due to the increasing number of herbicide-resistant weeds. In addition, weed management in high-value specialty crops encounters a unique challenge: the hesitancy of herbicide registrants to specify specialty crops on herbicide labels due to financial liabilities (Westwood et al., 2018).

Due to concerns associated with herbicide application, such as increased herbicide resistance and a growing demand for organic production, manual hand weeding has become an essential strategy in weed management. However, the expenses and difficulties of hand weeding make it one of the greatest weed management constraints that California growers face. The labor rates are impacted by recent California state legislation that increased the minimum wage to $15.00 per hour in 2022 and $16.00 in 2024 (Labor Commissioner's Office, 2024). Moreover, as a result of California Assembly Bill 1066 (2016), the overtime threshold, defined as the hours of work required before employees receive overtime benefits, in the agricultural industry has decreased to 40-h weeks and 8-h workdays in 2022 (Labor Commissioner's Office, 2022). Because of these increased labor protections, on-farm labor has increased in cost, and for organic crops and high-density planting, hand-weeding can cost more than $280 per acre for romaine hearts in the Central Coast (Tourte et al., 2023). In addition to labor costs, labor shortages have also been a long-standing trend in California agriculture as American agriculture increasingly competes with Mexican farms for farm labor (Taylor et al., 2012). This structural shift in the labor pool has caused fewer workers to be available for low-skill, low-wage agricultural jobs. Furthermore, human labor also is time-consuming and error-prone, eliminating only an average of 65 % to 85 % of weeds (Slaughter et al., 2008). To address the problems associated with conventional weeding methods, such as greater herbicide resistance and labor shortages and costs, the emergence of precision weeding technologies has become more prominent, supported by recent advancements in sensing technologies and artificial intelligence.

Precision weeding, targeted and selective removal of weeds using advanced technologies and equipment, has emerged as a compelling solution to address the limitations of conventional weeding methods in commercial agriculture. This method encompasses various techniques, including mechanical, chemical, and thermal/electrical weeding, presenting a versatile toolkit for growers. Many promising prototypes of precision weeding, covering all aforementioned techniques, have been achieved in academic settings (Bakker, 2009; Nasiri et al., 2022; Raja et al., 2023; Slaughter et al., 2008; Visentin et al., 2023; W. Zhang et al., 2022; Zou et al., 2023). In addition, early commercial operations have already proved the value proposition of fulfilling labor needs. One mechanical cultivator reduced the weed density by 27 to 41 % more compared to the conventional option (Fennimore et al., 2016).

The success of the precision weeding sector is dependent on the compatibility between the startups' value propositions and the growers' on-the-ground needs, which in this study is examined within the lenses of objectives, stakeholder interactions, and grower user journeys. This compatibility is heavily impacted by (1) social systems and institutional contexts and (2) individual grower perceptions and characteristics. In a USDA study about the adoption of precision agriculture for commodity row crops like soybeans, researchers found that drivers of adoption include grower participation in USDA programs (McFadden et al., 2023). Precision weeding adoption has been encouraged by the USDA Conservation Stewardship Program, which provides contract payments for environmental improvements. Technology adoption systems are often highly localized, with stakeholders optimizing their interactions with one another through curated local ecosystems. A study focused on institutional factors that impact startup formation uncovered significant relationships between most county-level variables (knowledge networks, policies, etc.) while much less significant ones between states, implying the importance of local ecosystems (Sunny and Shu, 2019). Beyond startup formation, localized networks for innovation can facilitate participatory, co-learning relationships between technology providers and technology users. Case studies of the adoption of decision support systems (i.e., technologies that help users understand biophysical responses to management changes) have shown that these technologies serve as a neutral meeting ground between scientists and growers, enabling the social context of co-learning cycles to influence individual learning (Jakku and Thorburn, 2010). Government-funded initiatives, as well as local ecosystem dynamics, help shape grower willingness.

Individual grower characteristics will also influence the success of precision weeding commercialization. Larger farm sizes are correlated with reduced risk aversion, the specialization of managerial labor, and lower per unit costs for equipment (McFadden et al., 2023). These characteristics lend to larger farms having a higher level of willingness to adopt new, riskier precision agriculture technologies. In addition, farmers also highly valued financial considerations such as economic returns and capital investment sizes. Characteristics that may impact whether Californian farmers adopt new technologies are their ages and social networks (Bandiera and Rasul, 2006). Though adoption rates are also positively correlated with older age, more experience, and the affordability to take risks, younger farmers may experience the lower cognitive cost of switching and thus be more likely to adopt new technologies (Bandiera and Rasul, 2006).

Furthermore, social networks impact the probability of adoption. This correlation can be exhibited through an inverted U-shaped in which the probability of adoption is low when only a few people in the network have adopted or almost all have adopted, but high when about half of the people in the network have adopted (Bandiera and Rasul, 2006). Thus, word-of-mouth could be the key factor in growers becoming aware of precision weeding technology, considering its adoption, and making an adoption decision. Precision agriculture technologies are often used in tandem. Therefore, precision weeding technology adoption rates could be higher for farmers who also use technologies such as GPS mapping and guidance systems (Schimmelpfennig, 2016).

Grower characteristics and decision-making processes cannot be fully understood without context on California growers and the other stakeholder groups involved in technology commercialization: startups and venture capital firms. In 2019, California had 69,900 farms with an average farm size of 348 acres (California Department of Food and Agriculture, 2020). This average farm size is smaller than the national average of 445 acres (United States Department of Agriculture, 2022). In 2017, Californian farmers had an average age of 59.2 years, and less than 6 % of all California producers, defined as farmers and ranchers, were aged 24 or younger (Kranz, 2019). Most farms–74 %–were owned by individuals, families, or partnerships. Although 10 % of farms were owned by corporations, less than 2 % were owned by non-family corporations (Kranz, 2019). Most farms are operated by California's 700,000 seasonal farmworkers (Minkoff-Zern and Getz, 2011). Our study design is limited to growers operating in Central California because of its dominance in Californian and American agriculture. The Central Valley produces over 250 crops with a value of $17 billion per year, an estimated 25 % of the nation's food, and in 2017, the Central Coast had over 400 vegetable farms and nearly 800 fruit and nut farms (California Water Science Center, 2024; Olimpi et al., 2019).

Startup companies are another key stakeholder playing a significant role in California's precision weeding ecosystem. Precision weeding startups have increased in popularity in the past few decades and have a positive growth trajectory, with the sector expected to grow by $268.75 million with a CAGR of 18.41 % from 2022 to 2026 (Technavio, 2022). On-farm research and pilot farms allow for more effective and quicker implementation on a farm level (Aarts et al., 2014). Precision weeding startups may be complementary to existing R&D efforts at larger corporations or seeking to disrupt current technologies or business models, potentially eroding monopoly power (Graff et al., 2021). However, incumbent agribusiness has retained their advantages of controlling supply chain and distribution standards. In addition, many startups seek out partnerships with incumbents for legitimacy and practical assets, such as manufacturing capacity (Fairbairn and Reisman, 2024). While startups often emphasize their value-based approaches and product innovation, they are inhibited by limited resources and look towards incumbents for process innovation (Hockerts and Wüstenhagen, 2010). Despite some startups toning down their ambitions after working with incumbents, many argue that VC-backed startups are a more efficient use of capital in comparison to global corporate agriculture R&D expenditures (Graff et al., 2021).

Investments from venture capital (VC) firms enable startups to take on the risky endeavors of developing and trialing novel technologies. In exchange for taking the chance on and providing capital to startups they ascertain as having exponential growth potential, VCs receive equity in the startups. VC investments in agri-food startups have accelerated in the past decade, with "twenty times more capital…invested in new agtech ventures in 2021 than 2012 (Asthana et al., 2022)." The average seed round for digital and precision agriculture startups is $3.8 million and the average funding increases to $117 million for Series D and later funding stages (Asthana et al., 2022). Up to 2006, global investments in agtech startups remained less than $200 million per year but then steadily grew until investments began exceeding $3 billion every year in 2010 (Graff et al., 2021). The large VC investments in agtech are a reflection of their general 'pioneering,' 'adventurous,' and 'disruptive' culture (Sippel and Dolinga, 2023). California is a natural geographical focus for our study considering the state's agtech innovation ecosystem has strong interparty dependence, the availability of venture capital, and a forward-thinking and tech-savvy consumer market (Mikhailov et al., 2021).

In addition to the three stakeholder groups directly involved in commercializing new technologies, government agencies are incentivized to be involved in the agricultural industry for economic reasons. In 2021, California's top twenty commodities produced over $44 billion in value (California Department of Food and Agriculture, 2022). For crop commodities, California regulates pesticide use through the California Department of Food and Agriculture and the California Department of Pesticide Regulation. The government historically played a more significant role in agricultural research and development through supporting agricultural research stations and academia as well as supporting philanthropic foundations (Graff et al., 2021). Outside of direct research and development financing, the public sector also serves as allies in cleantech startup innovation, particularly with licensing alliances with universities and developing markets through demand-pull policies (Doblinger et al., 2019). In addition, governments play a large role in the mobilization phase in particular because they select participants and set the criteria for funding (Hermans et al., 2019). With regards to precision weeding, the Governor's Office of Business and Economic Development (GO-Biz) has tax credit and sales tax exemption programs for the agriculture and agtech sectors. In the U.S., the USDA, other federal agencies, and state governments all administer public agricultural R&D funding (Blaustein-Rejto et al., 2022).

Although existing research has explored how growers adopt technological advancements through collaboration with commercialization partners, there has been limited focus specifically on the precision weeding sector. The growers' user journey could be different depending on the startup's business model (e.g., weeding-as-a-service versus a grower having to buy/lease the technology). Central California specialty crop growers face unique challenges compared to row commodity growers because specialty crops only account for 10 % of the U.S.' farm operations but shoulder the complexities of higher risk, variable costs (Neill and Morgan, 2021). A crucial gap exists within the body of literature about adoption networks regarding the relationships between stakeholders in the precision weeding ecosystem. Addressing this gap is imperative for elevating the advantages of precision weeding to the forefront of modern agricultural practices and comprehending the commercialization of precision weeding technologies, defined as the entry of such technologies into the mass market. This research study was motivated by the need to better understand how the relationships between stakeholders (California growers, agtech startups, and venture capital firms) in the precision weeding ecosystem impact the adoption of the technology. While other stakeholders, such as intermediary organizations like cooperatives, play a role in technology proliferation, we limited the scope of our study to the core groups directly involved in commercialization. The objectives were defined to address specific aspects of these relationships: (i) compatible motivations, investigating whether there are shared motivations among stakeholders, (ii) collaborative models, examining the effectiveness of existing collaborative models between stakeholders, and (iii) user journey, analyzing the user journey for growers adopting precision weeding technology and how technology adoption is impacted by other ecosystem players.

2. Methods

2.1. Interviewee demographics

The three core stakeholder groups in our study were (1) California growers, (2) agtech venture capitalists, and (3) venture capital-backed precision weeding startups. A supplemental interview was conducted with a representative of a government agency. Each of the interviewees was assigned an alphanumeric identifier. Most of the interviewees–15 out of 17–held managerial/senior positions (Table 1). The growers interviewed produce both conventional and organic crops, primarily specialize in leafy greens, including lettuce and cabbage, and have operations based in Central California.

2.2. Data collection

The data collection method employed for gathering textual data to answer the three objectives involved semi-structured qualitative interviews. This method was chosen over other qualitative methods, such

Table 1
Interviewee characteristics, including the category and their roles.

Category	Alphanumeric Identifier	Role	Category	Alphanumeric Identifier	Role
Venture Capital	V1	Executive	Grower	Gr1	Executive
	V2	Director		Gr2	Manager
	V3	Vice President		Gr3	Vice President
	V4	Executive		Gr4	Vice President
	V5	Analyst		Gr5	Vice President
	V6	Senior Director		Gr6	President
Startup	S1	Director		Gr7	Engineer
	S2	Head			
	S3	Executive			
	S4	Executive			

as surveys and focus groups, because open-ended exploratory questions best suit the perception-based and subjective research questions. Though the number of qualitative interviews required to draw legitimate conclusions is contentious, it is widely accepted that most novel information is generated early on in the data collection process in an asymptotic curve and then there is a steep drop off in new information. Analyzing three datasets—the first with 40 interviews and 93 unique codes, the second with 48 interviews and 85 codes, and the third with 60 interviews and 55 codes—researchers found that six to sixteen interviews could reach a median degree of saturation of 69 to 89 %. (Guest et al., 2020). Therefore, we conducted 17 interviews to comfortably predict high data saturation. Saturation assesses the rigor of qualitative sample sizes, indicating when additional data adds little or no new information to answering the research questions. Of the 17 interviews, we conducted interviews with seven Californian growers, five venture capital firms/accelerators, four precision weeding startups, and one government agency. A small sample size was effective in revealing the core categories of these lived experiences (Bernard, 2018).

Regarding participant recruitment, we used purposive sampling to certify that interviewees had experience within the precision weeding sector and held mid to high-level roles in their respective organizations, ensuring the validity of the data collected. The outreach process was through networking at a relevant in-person conference, cold emailing and social media messaging, and speaking with ‘connectors’ such as UC Cooperative Extension Specialists. In addition, we used the snowball sampling technique, whereby we asked interviewees to recommend additional study participants.

Due to logistical constraints, the interviews were conducted over video calls. Prior to the interview and following an explanation of the study objectives, informed consent was obtained via a form through WeSignature or verbally, allowing for voice recordings and transcriptions of the interviews. A caveat is that two of the interviewees’ informed consent forms did not allow voice recordings due to their companies’ legal directives but did allow for the interviews’ content and quotes to be used in this research study. The voice recordings were processed through the software Fireflies.ai (Fireflies.Ai, 2023) to acquire transcripts, which were manually proofread following the interviews. The number of questions asked was based on data and thematic saturation, a criterion used for discontinuing data collection and analysis (Saunders et al., 2018). To guarantee qualitative rigor, in this case, defined by the points at which no new themes are generated from the interviews, three open-ended questions were asked for each objective, adding up to a total of nine questions in addition to basic biographical questions. The interview questions, which are provided in the Appendix, were standardized with the same nine questions were asked for every participant. In addition, following semi-structured interviewing best practices, we asked participants to elaborate on answers and we dedicated more time to certain topics depending on interviewee expertise. These additional questions and structural flexibility enhanced feasibility and accommodated participant preferences.

2.3. Data analysis

The first step of thematic analysis was interview coding, in which the interview transcripts were run through the software ATLAS.ti (ATLAS. Ti, 2023), an AI-enabled qualitative data analysis software. An open coding method was used within the framework of grounded theory in which the textual data is used to uncover the responses of individuals to changing conditions and the subsequent consequences (Corbin and Strauss, 1990). A procedural characteristic of grounded theory is that data analysis must occur at the same time as data collection; the coding and analysis of the first interview should incorporate details of all potentially relevant information into the design of the following interviews (Corbin and Strauss, 1990). The similarities between the first interviews confirmed the efficacy of the interview questions.

For the first research objective about compatible motivations, the coding followed a simple coding process: when reviewing the first few participant transcripts, the data from the first set of three questions was cross-checked to identify recurring codes (Miles et al., 2014). Then, each additional transcript analysis added to existing codes, as well as potentially generating new ones. Detecting, classifying, and counting the presence of motivation-related codes quantified qualitative data, providing a more rigid content analysis (Vaismoradi et al., 2013).

On the other hand, a thematic framework was developed and the data was indexed against the framework for the second and third objectives (Goldsmith, 2021). This inductive thematic framework enabled comprehensive indexing and comparative analysis between the interviewees, allowing for the mapping of patterns. Because this study is about the complexity of stakeholder relations and how subjective perceptions leave tangible impacts, we used a structured yet non-mathematical approach for multi-level cognitive maps to answer the second research objective about stakeholder interactions. Cognitive maps are an example of soft organizational research (OR), representing mental models of stakeholders and the processes by which they gather information and make informed decisions that help them reach personal goals (Mingers, 2011). Cognitive mapping has been employed in many fields, including policy development and healthcare, to examine organizational decision making (Rees et al., 2018; Tanaka et al., 2020). Precision weeding is a suitable technology for this methodology because its stakeholders have varying, complex assumptions about weed management issues and the role of agtech as a solution. First, individual stakeholder maps were created from the individual interviews (micro level). Then, the individual cognitive maps were combined for each stakeholder group (macro level). To combine individual stakeholder maps to create stakeholder group maps, similar themes were overlaid, links were added between themes that individual interviewees contributed, and clustering was identified in the stakeholder group maps (Pidd, 1997). To answer the third research objective about grower user journey, we employed a similar soft OR approach to code concepts and present them in a “swim lanes” format. “Swim lanes” are a common industry method to map out the customer experience: how customers learn, interact, and respond pre-purchase to post-purchase (Reitsamer and Becker, 2024).

3. Results

The key results of this research revealed (1) the motivations behind adopting precision weeding technologies, (2) the financial, R&D, and social exchanges and collaborations between the stakeholders, (3) and the user journey for growers using the products and/or services of precision weeding startups. The key results included the varied motivations between the stakeholders and thus varied understandings of precision weeding's value, the controversial role of government in accelerating precision weeding technologies, and the user journey of growers adopting precision weeding technologies.

3.1. Compatible motivations

For the first objective about compatible motivations, the questions the interviewees answered differed slightly based on their stakeholder group. The motivations answered why precision weeding technologies should be within the future of weed management: why startups are developing, why growers are adopting, why VCs and CVCs are investing, and why government agencies are supporting precision weeding technologies.

Eleven indexed motivations were found in responses to the first objective. Fig. 1 shows the frequencies of these 11 indexed motivations per stakeholder group. The most common motivator was labor concerns, which was cited by 13 out of 17 interviewees (Fig. 1). Three participants (V4, Gr1, Gr2) added additional details about the labor pressures of organic farming in California, five participants (V1, S4, Gr3, Gr4, Gr7) spoke about the competitive labor market, three stakeholders (S4, Gr3, Gr4) mentioned budget difficulties due to California's increasing minimum wage, and two participants (V2, Gr7) addressed the role of precision weeding technologies in increasing the efficiency of labor. The interviewee Gr3 said that "as you lose your herbicide, you got [sic] to rely more on hand labor [and] mechanical labor." While they did not think that precision weeding technologies will ever completely replace hand labor, they speculate that growers will be able "to do a lot of heavy lifting with these newer mechanical weeders."

Following labor concerns, the second-most common motivator was cost, which was cited by 12 interviewees (V1, V2, V4–6, S1–4, Gr5–7) (Fig. 1). The motivator of 'meeting specific field conditions/needs' was cited by seven interviewees (V1, V2, S4, Gr1, GrGr2, Gr4, Gr5). Precision weeding technologies were also recognized for their ability to address specific field conditions or needs such as varying soil conditions,

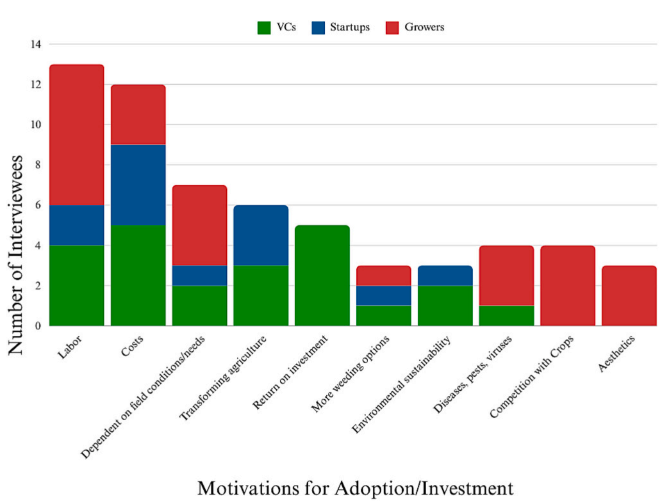

Fig. 1. Frequency of motivations for adaptation/investment shown as a stacked histogram. The most common motivations for supporting precision weeding were its potential to increase labor efficiency and reduce costs. Only growers were motivated by eliminating weeds that compete with crops and the aesthetic value of a 'clean' field.

banding, and thinning. Four interviewees (V5, V6, S2, S3) noted precision weeding's potential to 'transform agriculture' and to provide positive 'returns on investments.' Within the category of 'transform agriculture,' five interviewees, primarily startups, addressed precision weeding's potential to add value and increase farm profitability through sensors, additional data collection, advanced computation abilities, and automation.

The motivators of 'more weeding options' and 'environmental sustainability' were acknowledged by a few interviewees (Fig. 1). According to growers Gr3 and Gr4, the motivator of having additional weeding options through precision weeding technologies is partially a result of increased pesticide regulation in California, which may cause growers to lose access to certain types of pesticides. The government stakeholder added concerns about "glyphosate-resistant varieties out there…these weeds are mutating and they're resistant…then these new formulations come out…these spray-resistant weeds are mutating and getting worse and worse. I would love to see anything that can do targeted spraying or manual weeding come out to the front." Other interviewees added that weeds eventually adapt to weed management tools and thus effective regimes vary both temporally and in terms of products used. Three interviewees explicitly mentioned 'environmental sustainability' (V2, V3, S3) but the umbrella of environmental sustainability includes the benefits of (1) fewer inputs and chemicals, cited by six interviewees (V1, V2, V4–6, S3), (2) animal and human health outcomes, cited by three interviewees (V3, V4, S3), (3) soil conservation, cited by one interviewee (V2), and (4) following the United Nations' Sustainable Development Goals, also cited by one interviewee (V3).

The motivation for aesthetics was evoked by three out of seven of the growers (Gr1–3) and refers to the negative impact of weeds on the aesthetic or visual appeal of the fields (Fig. 1). Interviewee Gr2 shared that "growers like their fields to look nice and so [weeds] are also removed for aesthetic reasons" and interviewee Gr3 added that weeding is also a preventative measure so that harvesters do not accidentally harvest weeds in addition to the crops.

Though there was a consensus across all stakeholder groups about the importance of labor concerns, other motivators were more polarized (Fig. 1). For the most part, only growers expressed concerns about weeds harboring diseases, pests, and viruses, weeds competing with crops for resources, and the aesthetic value of weeding. In addition, only growers mentioned–under the motivator of 'more weeding options'–that precision weeding adoption was partly driven by concerns that increased regulation in California could cause growers to refuse access to herbicides.

3.2. Stakeholder interactions and limitations

To answer the second sub-question regarding collaborative models between stakeholders, the comprehensive indexing of themes revealed that the average number of constructs, defined as key words and/or concepts that address stakeholder interactions and limitations, for all individual interviewees was 60. Excluding labels and descriptors, the startup stakeholder group produced an average of 59 constructs, growers had 58 constructs, and VCs had 63 constructs. All stakeholder groups produced a similar range of constructs, indicating the universality of the interview questions asked.

Growers identified several blockers to adoption, such as competition between growers, old-school mentalities, and a lack of connection between startups and growers (Fig. 2). Precision weeding requires the bandwagon effect for growers to want to try new technologies. However, competition between growers might hinder the bandwagon effect because growers may not wish to share their competitive advantages with their neighbors. This stakeholder group also asserted that many growers view working with startups as a high-risk endeavor, citing the high capital expenditures of most precision weeding machinery and the history of unsuccessful agtech startups. Because of these perceived risks, the multiple farm managers who work at one company may disagree

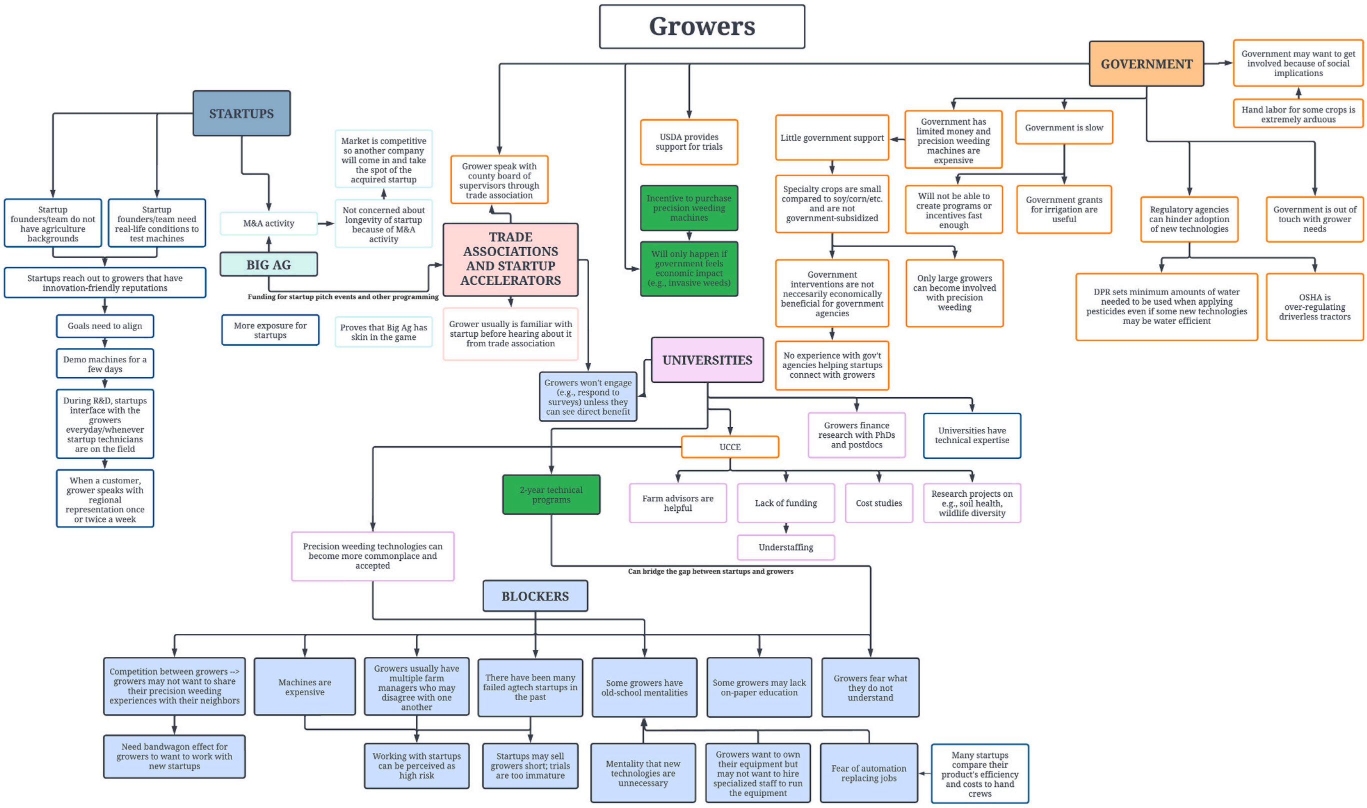

Fig. 2. Grower stakeholder group cognitive map. This cognitive map reveals that growers feel like there is little support from the government in helping them connect to precision weeding startups and adopt precision weeding technologies within their operations. Additionally, some growers are wary of precision weeding startups because of (1) the high-risk profile of startups and (2) some startups not having founders and employees with agricultural backgrounds.

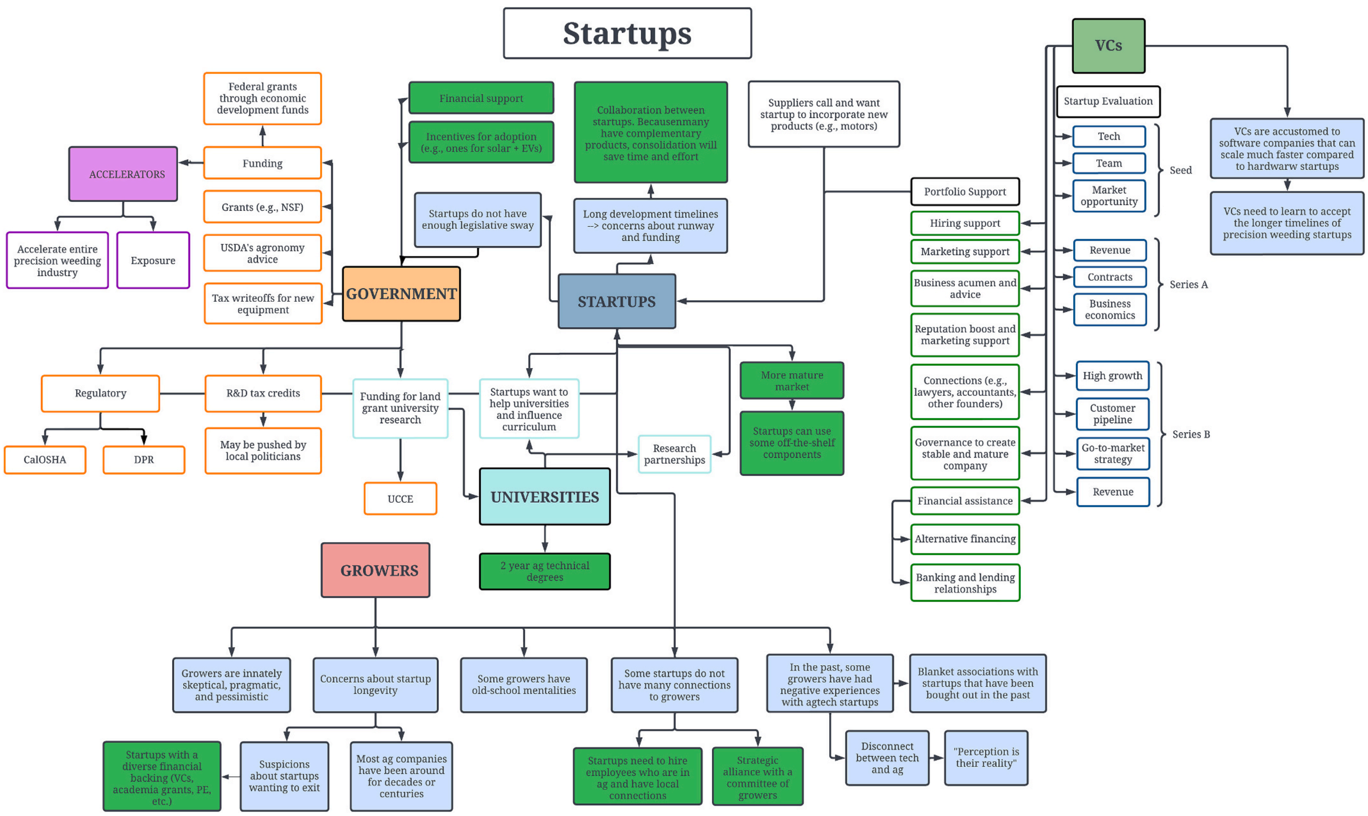

Fig. 3. Startup stakeholder group cognitive map. Startups have a symbiotic relationship with VCs, interact with governments via UCCE and funding/grant opportunities, and use strategies like having strategic alliances with grower committees to counteract initial grower skepticism.

with one another and prevent adoption. Startups also added that concerns about startup longevity are especially intensified because most traditional agricultural companies, such as John Deere, have been around for decades or centuries (Fig. 3).

Furthermore, growers perceived old-school mentalities and a potential lack of on-paper education as a blocker to the adoption of precision weeding technologies (Fig. 2). Some may view new technologies as unnecessary and the mark of 'true' growers as putting in the hard work twelve hours a day, seven days a week. In addition, because many startups compare their products' efficiencies and costs to hand crews, some growers fear automation replacing their jobs. Although many growers want to own their own equipment, they may be reluctant to hire specialized staff to run the equipment.

Startups and VCs also mentioned and expanded upon the growers' urge to own their own equipment, coming into conflict with the weeding-as-a-service business model that some startups have ventured into. Interviewee V2 also added that "eventually farmers need to own the equipment [because of] timing. As your operations become larger, timing becomes absolutely critical. As you grow different crops in variable environments, you need the machine. You may be in a field and discover; I need the machine right now and you phoned the service guy and he's got three farms ahead of you." Other startups have turned to the weeding-as-a-service business model to abate prohibitive capital costs and to ensure the machinery out on the fields are up-to-date with the startups' latest developments (Fig. 3). S3 illustrated this point by saying "the first-generation spray that we've built is like the iPhone 1, and technology is changing so fast that I know in three months I'm going to have iPhone 3 coming out." S3 added that startup-centric reasons for the service model include allowing the startups to have constant access to new data and the ability to quickly relay failure points to the R&D teams. In addition, the weeding-as-a-service model provides a more intimate experience between the startups and the growers, enabling startups to conduct in-depth customer discovery for their current products and future ideas.

The startup interviewees brought up the limitation that some startups lack connections to growers (Fig. 3). Many proposed that startups need to hire employees who have worked in the agricultural industry and have local connections, while some also brought up that startups could develop strategic alliances with a committee of growers. Another startup limitation was the long timelines for hardware research and development, raising concerns about financial runways and funding. Some startups asserted collaboration between startups could alleviate runway fears as many startups have complementary products; consolidation will save time and effort.

According to VCs, startup-university and grower-university relationships are often difficult to navigate and are not always advantageous (Fig. 4). With startup-university partnerships, patent battles may sometimes emerge, particularly if the startup's distinguishing technology directly spun out of university-sponsored research. In terms of how growers interact with universities, university research topics and trial designs are usually limited in scope and not perfectly aligned with the goals of the growers.

The startup and VC relationship was also described in-depth by both stakeholder groups (Figs. 3 and 4). For both parties, interviewees agreed

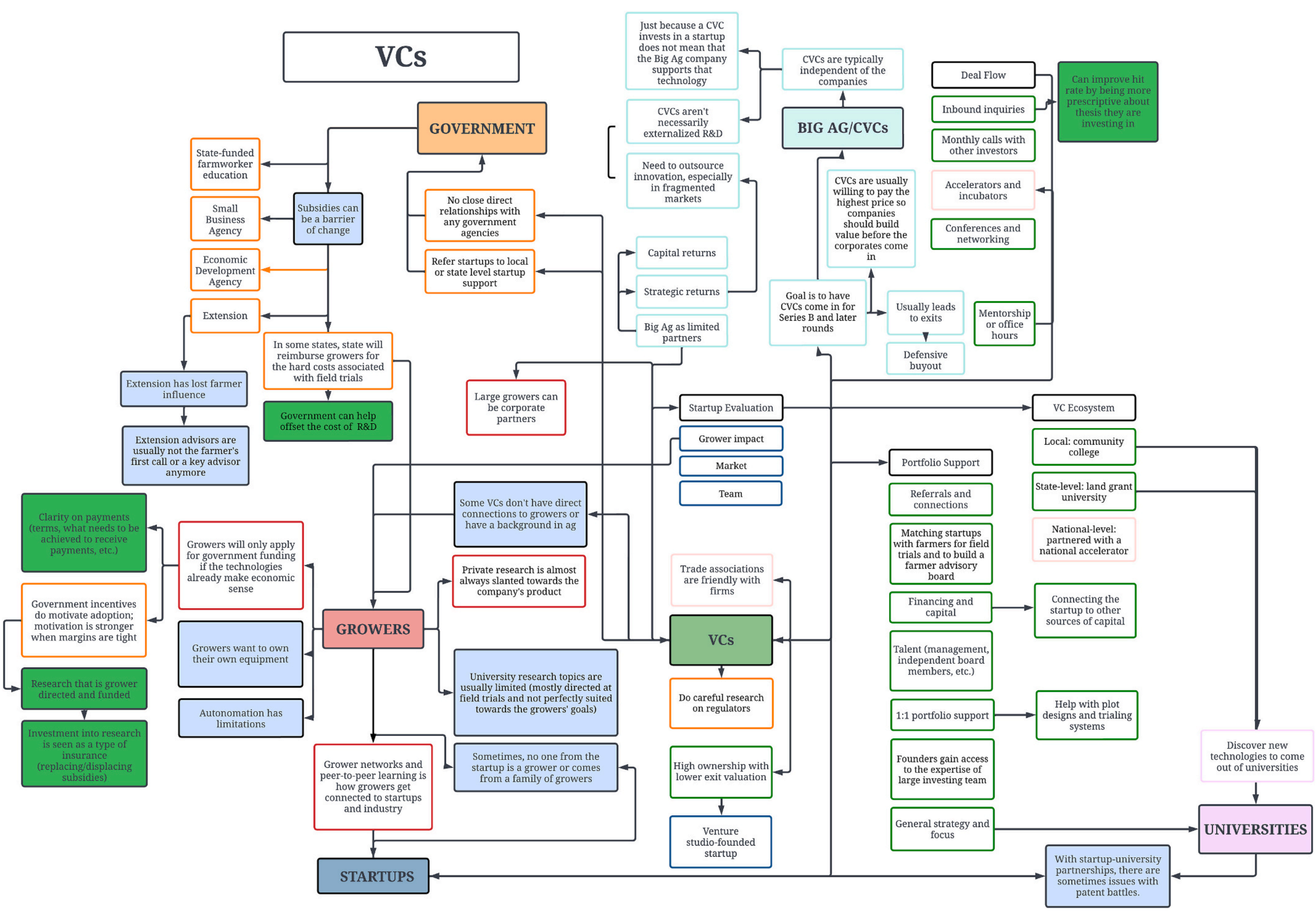

Fig. 4. VC stakeholder group cognitive map. VCs have a symbiotic relationship with startups, and some which specialize in agtech will differentiate themselves by emphasizing their agricultural expertise. CVCs, a subset of VCs, have varying levels of alignment with their parent organizations but all are responsible for achieving strategic returns through engaging with innovative startups.

that portfolio support from VCs to startups includes hiring and marketing support, business acumen and advice, connections to lawyers, accountants, and other startup founders, advancing governance to create stable and mature companies (by, for example, participating in the startup's board of directors), and financial advising. VCs also mentioned hands-on, agriculture-related support such as matching startups with growers for field trials, building a grower advisory board, and helping with plot designs and trialing systems. Beyond portfolio support, VC ecosystems also vary in scale from local to international. When VCs evaluate which startups to fund, the criteria depend on the stage of the startup. During the seed stage, VCs judge startups based on their technology, team, and the extent to which the startup has a believable market opportunity. Moving towards the Series A funding round, VCs begin to care about unit economics, proof of traction through contracts and letters of intent, and revenue. At the Series B stage, VCs continue to value revenue metrics and begin to look for established customer pipelines, go-to-market strategies, and proof of high growth companies.

All three stakeholder groups had varying opinions of the role of government in the precision weeding ecosystem. Under existing conditions, growers viewed the government as offering little support and being out-of-touch with grower needs. Because specialty crops are a small percentage of America's total agricultural production due to large commodity crops like rice, soy, and corn, government intervention for specialty crops would not provide as positive of a return on investment. While the government is slow, some of the growers did commend effective government funding for irrigation. However, in the future, because hand labor for weeding is arduous, some growers have hope for increased government support because of precision weeding's positive social implications. Startups viewed government involvement as limited to grants and the USDA's agronomy advice. Though pushed by local politicians, particularly in Salinas Valley, R&D tax credits remain trivial. In addition, startups and VCs noted the role of regulatory agencies such as CalOSHA and the Department of Pesticide Regulation.

In connection to the government, all three stakeholder groups mentioned government funding for land grant university research and the UC Extension system in a positive light. Some startups mentioned that they want to become more involved with universities to influence the curriculum and develop two-year technical degrees to combat workforce constraints in agtech implementation. However, some interviewees, such as V2, voiced that the Extension has lost grower influence and that now, Extension advisors may not be the farmer's first call or key advisor anymore. Similarly, growers felt that though Advisors are helpful in educating and advising, a lack of funding and relatively low salaries have prevented the UCCE from gaining more influence over grower behavior and precision weeding adoption.

In total, the thirteen concepts mentioned most in the interviews were identified to measure the overlap of themes between the stakeholder groups, (Fig. 5). Five described current limitations preventing precision weeding from proliferating, four involved the role of government in promoting precision weeding, three concerned the interactions between startups and VCs, and one was about the role of large corporate farms. Some concepts were more polarizing than others, as demonstrated by the color imbalances between the bars for each concept. Concepts about

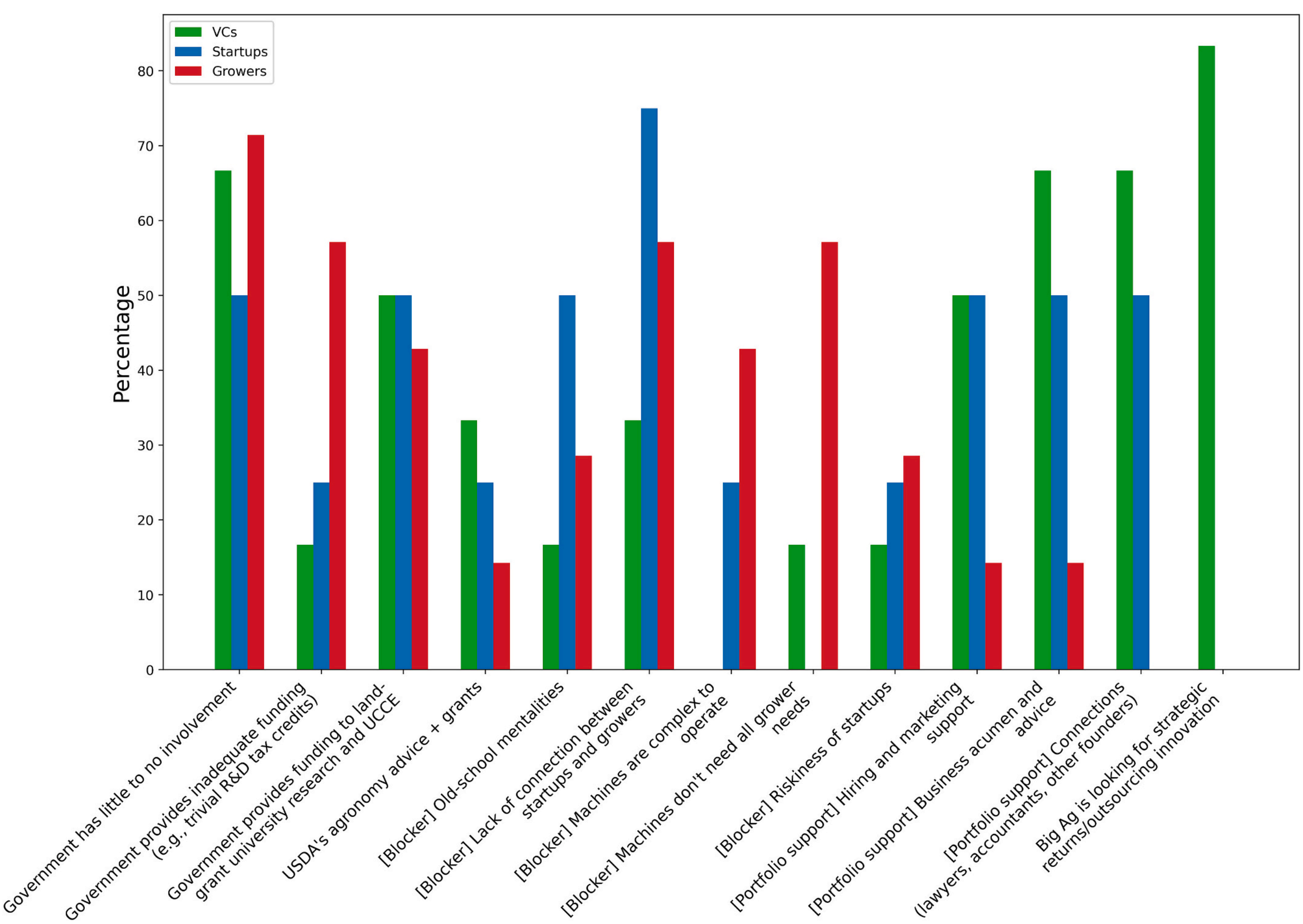

Fig. 5. Thirteen most common themes. The thirteen most common themes brought up by interviewees related to government interactions, blockers to adoption, and the portfolio support that VCs provide startups.

the limited involvement of government and the role of the government in funding land-grant university research and the UCCE were agreed upon by all three stakeholder groups. However, only VC interviewees (V1, V2, V3, V4, V5) addressed the concept of 'Big Ag is looking for strategic returns/outsourcing innovation' to explain why large corporate farms engage with precision weeding startups. Additionally, the complexity of the machines to operate was brought up as a blocker by the startups and the growers, but not VCs.

3.3. Grower user journey

To visualize the results about the third objective, interviewee responses were mapped onto a user experience template, colloquially known as 'swim lanes.' After overlaying the results for growers, the most

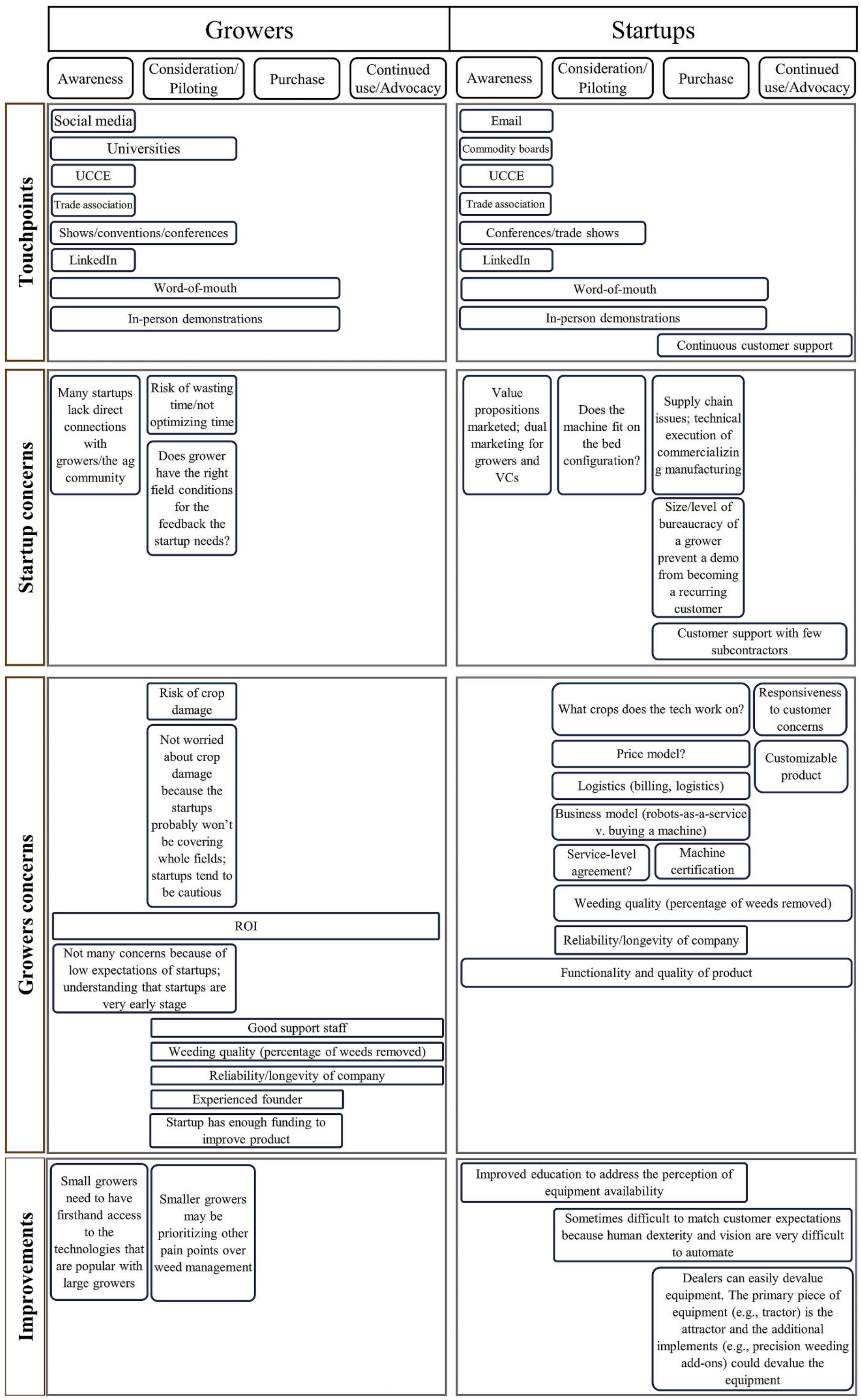

Fig. 6. User journey of adoption of precision weeding technologies according to growers and startups. "Swim lanes" are a common industry method to visualize customer journeys and how customers engage with companies over time. In the 'awareness' phase, startups and growers often first interact via social media, traditional marketing efforts, and word-of-mouth. Then, conferences and in-person demonstrations help growers better understand the startups and lead to pilots. Both stakeholder groups begin to be concerned with weeding quality and the reliability/longevity of the companies involved.

common touch points identified in the growers' awareness phase were social media, in-person networking through conferences and conventions, and collaborations with universities.

Growers perceived startups to be concerned about their lack of connection to the agricultural community, the risk of wasting time with unideal pilots, and ensuring the grower has the right field conditions for what the startup needs feedback for (Fig. 6-growers). On the other hand, startups perceived their concerns to be (i) the dual marketing of value propositions towards growers as well as their investors, (ii) supply chain issues that may limit their technical execution of commercializing manufacturing, and (iii) large growers having bureaucratic issues that prevent demonstrations and pilot projects from becoming recurring customer relationships (Fig. 6-startups).

During the pilot phase, growers perceived themselves to be concerned about the risk of crop damage, support staff, startup longevity, and startup quality and capabilities (Fig. 6-growers). During the piloting and purchasing phases, startups perceived growers' concerns to be the price model, logistics, weeding quality, and the startup quality and capabilities (Fig. 6-startups). While many startups were concerned about matching customer expectations because imitating human dexterity and vision is technically challenging, one grower explicitly did not have concerns in the piloting phase because they have realistic expectations: "I don't expect it to be like a John Deere tractor that's just going to come out and be perfect and do everything that's expected. I get it with technology companies that when it's going to come out, it may suck."

Most of the areas of improvement brought up were in the consideration/piloting phase. Growers felt that points of improvement in their user journey included the prioritization of larger growers over smaller growers: smaller growers should have the same access as larger growers have to new technologies (Fig. 6-growers). In addition, smaller growers may value other pain points, such as food safety, over precision weeding (Fig. 6-growers). Startups felt that improvements could be made by educating growers about misperceptions about a lack of equipment availability within weeding-as-a-service business models. Some startups were also concerned about the ability of dealers to devalue the primary piece of farmers' equipment, such as a tractor; the additional implements, such as precision weeding add-ons, could devalue the equipment (Fig. 6-startups).

4. Discussion

4.1. Labor and sustainability as main motivators

The most common motivations for precision weeding technology adoption were labor concerns, environmental sustainability, costs, and return on investments. Growers were the most vocal and detailed about the shortage of labor motivating their interest in precision weeders. Because of the increase in minimum wage and AB 1066 qualifying farmworkers for overtime pay, growers and producers are growingly concerned about labor regulations (Quandt, 2023). These increased labor expenses push producers to increase on-farm efficiency and mechanization, particularly on vegetable and organic farms. California growers' issues with labor scarcity and thus increased labor costs has been a long-standing trend that also contributed to early mechanization during the 20th century. Because of California's niche growing conditions, there was the advent of new gasoline tractors and mechanical pickers and harvesters (Olmstead and Rhode, 2017). Now, labor scarcities are especially pressing because of California's large production of specialty crops.

Labor expenses are also especially pertinent because of the state's strong organic sector and its associated costs. In 2019, data from the California Department of Food and Agriculture's State Organic Program found that California's organic sector is growing: organic acreage has increased from 1.8 million acres in 2014 to 2.6 million acres in 2019, and in 2019, organic products in the state sold for more than \$10.4 billion (State Organic Program, 2020). Additionally, California's organic production made up 40 % of all organics in the U.S., indicating the state's importance as the trailblazer of organic agriculture (State Organic Program, 2020). This increase in organic production has arguably been fueled by support from the State Organic Program, a regulatory and educational department within CDFA which has, for example, implemented cost share programs for USDA certification (Klonsky, 2010). In addition, the consumer preference for organics has driven this trend: multiple studies have demonstrated consumers' willingness to pay premiums for organics, with the market demand influencing grower decision making (Yue and Tong, 2009). However, organic farms face logistical and operational challenges because they employ more workers per acre. A survey of organic farms revealed that farms that have less than half of their land in organic production have fewer direct-hire workers per acre, 0.58, in comparison to farms with more than half, 0.84 (Strochlic et al., 2008). Similarly, another study found that compared to conventional farms, organic farms have both more workers per acre and a higher proportion of full-time employees to seasonal contractors (Finley et al., 2017).

Interestingly, despite copious literature on the positive correlation between increased costs—particularly from labor—and organic farming, the results of this study align more closely with literature suggesting that digital technologies are often closely adapted to conventional/industrial farming practices. All the growers we interviewed produce both organic and conventional crops and most startups we interviewed still included herbicides in their weed management regimes. The trend of agricultural technologies being more suitable for conventional agriculture has been shown in the use of big data, an aspect of digital agriculture defined as large sets of heterogeneous data. While harnessing big data has proven environmental and economic benefits, access may not be realistic for small-scale farmers, further widening the accessibility gap between industrial players and more vulnerable ones (Lioutas and Charatsari, 2020). Elaborating on this accessibility gap, a review of digital agriculture revealed that top-down technological development, as opposed to farmer-driven initiatives, often are designed for very specific production systems (e.g., a precision weeding technology may only be required during specific times and for one row crop) (Rotz et al., 2019). In addition, agricultural machinery exhibits economies of scale at the farm level, favoring larger-scale farms (Birner et al., 2021). Beyond the larger farm size associated with conventional growers, technological solutions may not target the needs of organic growers. A study found that digital technology use for production was underrepresented on organic farms because of a mismatch in the technology solution and the grower needs (Schnebelin, 2022). For example, GPS deployment may help a conventional grower save on diesel, fertilizer, and weed killer, but it will only help an organic grower save on diesel. As a result, literature suggests that digital agriculture, including precision weeding technologies, may be adapted more towards conventional agriculture despite the labor stresses felt by smaller-scale, organic growers.

All venture capitalists interviewed were motivated by environmental sustainability while only one grower mentioned it. This venture capital emphasis on environmental concerns such as soil quality, water quality and quantity, and unsustainable practices spur agtech investments. Investors not only valued financial returns but were also motivated by social impact and environmental returns (Dutia, 2014). Because of the venture capital emphasis on environmental concerns, startups may align themselves similarly to raise funding. In a study examining how agri-food tech startups pitch themselves to venture capital firms, researchers found that VC firms make investment decisions not only on the substance and hard facts, but also based on the performance and cultural signaling of the pitch (Fairbairn et al., 2022). Therefore, precision weeding startups may drive narratives of social entrepreneurship and sustainability to develop 'visions of desirable futures' and add moral justifications to their technologies (Sippel and Dolinga, 2023). Paralleling such startup pitches are the mission statements of agri-food tech investors, which often combine profit and purpose (e.g., promoting higher-efficiency food systems while also fighting climate change) (Sippel and Dolinga, 2023). Despite both stakeholder groups emphasizing sustainable stances, these aspirations may fall short: 'techno-fixes' are overly simplistic and cannot realistically correct global food system challenges and the investors' ROI requirements may curb ambitions (Klerkx and Villalobos, 2024).

4.2. Government interactions

Considering the varying views of government conveyed by the interviewees, the political identities of the interviewees may influence their views on the effectiveness and ideal roles of government. A common sentiment across stakeholders was that the state government reacts too slowly to be effective. Growers also expressed an increased distrust of government, a trend consistent with the general population (Kaufman, 2016). A study using ANES survey data found a shift from democratic identification to independent and conservative ideologies (Kaufman, 2016). In addition, in Imperial County, the most impactful work-related stressor for farmers and ranchers were unpredictable factors like government regulations (Keeney et al., 2021). Though growers felt that the government did not understand the realities of agriculture, many actively advocated and were involved in agricultural leadership efforts (Quandt, 2023). These generally negative sentiments from growers towards the government are juxtaposed by the involvement of the public sector in the digitization of agriculture. A case study examining precision dairy farming in Australia found that public R&E played the largest roles, relative to private R&E, in market formation and the creation of legitimacy (Eastwood et al., 2017). In particular, the public sector galvanized a community of interest around precision dairy farming and developed the National Livestock Identification Program to establish industry standards (Eastwood et al., 2017). In addition, an example of public action promoting digital agriculture is the regulatory pressure against glyphosate use incentivizing industry players to decrease chemical inputs (Birner et al., 2021). Considering the parallels for all on-farm technology adoption, existing literature about digital agriculture and the public sector can be contrasted by our case study of precision weeding in which the startup-VC-grower matrix does not consider government interactions as a factor for technology adoption. Growers characterized some aspects of government regulation to be out-of-date with current technological trends and emphasized that government intervention has not played an active role in expediting precision weeding technologies. Though both VCs and startups called out economic development funds and locally-supported R&D tax credits, both stakeholder groups did not consider these government interactions to be as effective as industry-led programs.

Another theme that emerged regarding the second objective is that the ideal role of government should be more hands-off because companies should find success in the free market. Some did bring up the benefits of clearly defined funding opportunities to reduce the friction of growers seeking government funding. A study using financial datasets of over 32,000 companies found that subsidies were only effective for short-term innovation while tax credits were favorable on both short and long terms (J. J. Zhang and Guan, 2018). Subsidies are direct fiscal measures where the government is the project decision maker whereas tax credits are indirect fiscal measures whereby companies can choose their own projects and the direction/purpose of the innovation activity (J. J. Zhang and Guan, 2018). However, all interviewees agreed that tax credits and subsidies should not be the primary driver or business case for precision weeding adoption. Technology providers (startups) should already clearly match the needs with the technology receivers (growers). Government support should only fill in initial financing gaps as startups works towards achieving economies of scale.

4.3. Business model preferences

Interviewees from all stakeholder groups brought up the grower preference for equipment ownership, going against service-based business models. Some precision weeding startups are using or have tried in the past to employ the weeding-as-a-service, recurring revenue model, whereby customers pay the startups for each instance of the service of weeding. Owning equipment is preferred, especially accounting for the time sensitivity of some agricultural operations. Additionally, government loans and incentives, such as USDA Farm Service Agency Direct Farm Ownership Loans, help growers enter long-term leases or purchase their own equipment. Because of this strong equipment-owning preference, grower skepticism towards a weeding-as-a-service business model can hinder the growth of precision weeding startups. However, literature shows that recurring revenue models, as opposed to the direct sales model, have the advantages of significantly lower capital costs and lower payments compared to traditional loan structures, especially considering that weeding equipment remains idle for the majority of the year (BIS Research, 2019). Furthermore, subscription models give growers access to the newest and latest technologies, sharply decreasing the replacement cycle periods (BIS Research, 2019). These two revenue models are also not binary: recurring revenue models can derisk the use of new precision weeding innovations, with an initial subscription service proving the value of the technology, before growers transition to purchasing the equipment at the end of the contracting period (Gil et al., 2023).

Beyond one-time purchasing and recurring revenue models, shared equipment pools managed by grower cooperatives and/or community organizers can derisk growers trying expensive technologies. An expansion of informal peer-to-peer networks, cooperatives can own equipment on behalf of their members and operate at cost. Non-profit or community-based organizations and equipment sharing businesses can also provide such services (Gilbert, 2018). Though growers typically prefer equipment ownership, case studies on equipment sharing arrangements, particularly in Europe, have assuaged timing-related fears. For example, a Swedish cooperative used 20 years of data to calculate the economic losses from performing a field operation at a sub-optimal time. Their results found that the cost savings from shared equipment still outweighed 'timeliness costs' (Gilbert, 2018). In addition to the non-purchase option that cooperatives provide, contractor services can also be a mode for equipment deployment. The contractor does not necessarily have to be the manufacturer (i.e., startups offering weeding-as-a-service). Instead, equipment dealers or other businesses can train third-party technicians and offer contractor services. In fact, Bavarian small-scale farmers preferred both contractor services and shared equipment models over equipment ownership and working directly with the manufacturer (Spykman et al., 2021). Despite such literature proving a preference for cooperative sharing pools, the interviewees of our study did not express similar views.

4.4. Grower user journey

The third objective regarding the user journey of growers adopting precision weeding technologies examined grower and startup concerns and touchpoints from awareness to continued use and advocacy. Both startups and growers emphasized in-person networks as the most important touchpoint and platform by which growers learn about new technologies. The influence of peer-to-peer networks brings up the question of perceived social risks: studies have shown that farmers who believe in combating climate change in their operations are concerned about the risk of negative social perceptions and thus reduced access to peer-to-peer networks (Petersen-Rockney, 2022). In this study, many Northern California farmers implemented climate adaptation farm management practices, such as water-effective irrigation. However, many remained sensitive about the negative political/social framing of climate change, strongly justifying their environmental adaptive actions with co-benefits, such as economic efficiency (Petersen-Rockney, 2022). Additionally, in a pollination management study in Michigan, researchers uncovered several large advice networks in which growers can reach other growers and their partners in a maximum of two to three hops and that 26 % of all communication mapped was from grower-to-grower (Garbach and Morgan, 2017). In our study, growers cited word-of-mouth from their peers as one of the key touchpoints influencing their journeys through the awareness, consideration, and purchasing phases. Because many startups lack direct connections with growers, growers may look towards their peers to vet potential startup partners. In addition, aligning with Petersen-Rockney (2022), the competitive landscape of specialty crops lend itself to the high stakes of intra-stakeholder dynamics and social perceptions.

5. Conclusion

For the first objective about the compatible motivations between precision weeding stakeholders, we found that the most common motivator was labor concerns, which was cited by 13 out of 17 interviewees. Some stakeholders added additional details about the labor pressures of organic farming in California, the competitive labor market, the hiring budget difficulties because of California's increasing minimum wage, and the role of precision weeding technologies in increasing the efficiency of labor. Other commonly cited motivations were costs and precision weeding's potential to 'transform agriculture.'

Answering the second objective of collaborative models between stakeholders and their limitations, we found that the grower-identified blockers to adoption included competition between growers, old-school mentalities such as equipment ownership, and a lack of connection between startups and growers. Additionally, startups and VCs also mentioned and expanded upon the growers' urge to own their own equipment, coming into conflict with the weeding-as-a-service business model that some startups have ventured into. The startups agreed with the limitation that some startups lack connections to growers and suggested a few solutions: hiring employees who have worked in the agricultural industry and have local connections and startups developing strategic alliances with committees of growers. Both startups and VCs discussed their symbiotic relationship: VCs provide startups with portfolio support to accelerate business growth and mature company governance in exchange for equity. Exclusive to the agricultural industry, some VCs spoke to their role in providing startups on hands-on, agriculture-related support such as building a grower advisory board. All three stakeholder groups had varying opinions of the role of government in the precision weeding ecosystem. While all agreed that government-funded university research and the UC Cooperative Extension were helpful, growers and startups viewed all tiers of government as being out-of-touch with grower needs and not providing enough R&D support to accelerate the adoption of precision weeding. The growers' distrust of government is consistent with existing research.

Regarding the third objective about the grower user journey, the most common touch point identified in the growers' awareness phase was in-person networking, consistent with existing research about the influence of peer-to-peer networks in spreading information. Most of the areas of improvement were in the consideration/piloting phase, such as educating growers about misperceptions towards weeding-as-a-service business models, such as lack of equipment availability.

As for the study's limitations, the experimental design purposely was exclusively semi-guided qualitative interviews, as opposed to a mix between interviews and surveys, to examine in-depth perspectives and experiences. A limitation inherent in this experimental design was a lack of breadth, as the stakeholders interviewed in this study did not thoroughly represent the entirety of California's precision weeding ecosystem, especially considering our focus on only three stakeholder groups. Future research could expand beyond our interview approach to include willingness-to-pay surveys to ascertain grower attitudes towards precision weeding. In addition, future research can broaden our research objective of compatible motivations to develop joint value propositions. Better aligned value propositions will help startups communicate with growers and may influence startup R&D direction to better suit grower needs. Another limitation we faced with the interviews is that the agtech investing space, particularly for investors who have interests in California agriculture, is quite small. Because 'all VCs know each other,' some venture capitalists we interviewed or reached out to interview had concerns about anonymity and/or having diverse-enough viewpoints. Additionally, government outreach proved difficult with many potential interviewees canceling after learning about the informed consent conditions. However, this limitation was not a significant hindrance as the three core stakeholder groups did not include the government. This does raise a potential future research direction that more directly examines agriculture-related government endeavors and public-private collaborations. A limitation in an aspect of our data collection method was concerns regarding interview standardization. Though we followed a guide of pre-prepared questions for each objective, some interviewees cut the interview short while some were very generous with their time. The shortest interview was twenty-three minutes while the longest one was over an hour and a half. Therefore, in our results, we only featured stakeholder group maps, not individual maps.

The broader implications of the study are for the governmental role of encouraging new technologies and the usage of cognitive mapping for agtech ecosystems. Precision weeding technologies respond to grower needs with conventional weed management. Resulting from labor pressures, the rising costs of chemical inputs, and market and government pushes towards environmental sustainability, California growers are pursuing alternative techniques such as buying machinery from new precision weeding startups. However, the adoption of precision weeding technologies is at times hindered by negative growers' perceptions of startups and new technologies. In addition, despite strong public sector involvement in other digital agriculture sectors, this study found relatively low government involvement in precision weeding. Therefore, the policy implications and our recommendations are less on the regulatory side, but more so for governments to have a soft role in shaping standards and establishing legitimacy for new technologies.

The cognitive mapping presented in this study can be applied to other emerging agtech ecosystems. Because most venture capital firms that invest in precision weeding also invest in other agtech startups or industry-agnostic hardware/deeptech startups, the interactions between agtech startups and venture capital firms may remain similar. However, future research may find varied interactions between the startups and growers. A future research direction may apply the same stakeholder mapping/qualitative interviewing methodology to other emerging agri-food technologies in regions outside of California. Like precision weeding technologies, crop harvesting robotics for specialty crops have achieved impressive prototypes in academic settings (Li et al. 2024; Tituaña et al., 2024; Zhang et al., 2022). Because of the similar high hardware costs and relatively low on-field use throughout a season, single-purpose autonomous robots are a suitable candidate for this study's methodology. A study examining autonomous robots for soft fruit cultivation in the UK discovered that labor shortages are driving farmers to become interested in and optimistic about the potential of autonomous robots in picking, disease treatment, and harvesting (Rose and Bhattacharya, 2023). While our results found that growers were cognizant of the limitations and lower technology readiness levels of the startups' initial prototypes and were sometimes willing to adjust their expectations accordingly, some studies have shown a deeper involvement between these two stakeholder groups at this early demonstration/piloting stage. For example, a project in New Zealand had been researching collaborative design efforts for a robotic apple harvester. Because orchards must be 'robot-ready,' such as having denser rows with trees lying flat against trellises, researchers found that some orchardists have been adjusting their landscapes accordingly to accommodate future technology adoption (Legun and Burch, 2021). Beyond leafy greens and fruit orchards, site-specific management is ideal for the heterogeneous nature of vineyards and our study's methodology can be applied to precision viticulture. As the technology and user readiness of precision agriculture hardware develops, stakeholder mapping can identify gaps in the existing ecosystem and offer both public and private entities opportunities to develop mechanisms that accelerate technology adoption.

CRediT authorship contribution statement

Christiana Wong: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Moghimi:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104152.

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