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Journal
Agroecology and Sustainable Food Systems, 48(3)

ISSN
1044-0046

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Publication Date
2024-03-15

DOI
10.1080/21683565.2024.2303454

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Agroecology and Sustainable Food Systems

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/wjsa21

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To cite this article: Estelí Jiménez-Soto, Madeleine Fairbairn, Joji Muramoto & Carol Shennan (25 Jan 2024): Agriculture against the wall: barriers and opportunities for agroecological transitions in California's industrial agricultural landscapes, Agroecology and Sustainable Food Systems, DOI: 10.1080/21683565.2024.2303454

To link to this article: https://doi.org/10.1080/21683565.2024.2303454

Published online: 25 Jan 2024.

AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS
https://doi.org/10.1080/21683565.2024.2303454

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Agriculture against the wall: barriers and opportunities for agroecological transitions in California's industrial agricultural landscapes

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ABSTRACT
Agroecology emphasizes a shift from low diversity, high chemical input farming to more biodiverse agroecosystems cultivated in conjunction with natural ecosystem processes and embedded in socially just relationships. Yet achieving such agroecological transitions presents enormous challenges in industrial agricultural landscapes dominated by consolidation and overproduction. We examine both the challenges and the opportunities for agroecological transition in one particular industrial agricultural context: the fumigant-dependent strawberry production of California's Central Coast. We do so by exploring adoption of Anaerobic Soil Disinfestation (ASD), an agroecological alternative to fumigation which has shown considerable promise but has been historically underutilized. Building on previously identified "domains of agroecological transformation," we characterize the enabling and disabling conditions for agroecological transitions in California's agricultural landscape. Through semi-structured interviews with farmers, extensionists, and industry stakeholders we uncover significant regime lock-ins: most prominently insecure land tenure and unequal access to land, unequal systems of exchange, and a culture that favors silver bullet narratives and top-down knowledge transfer; as well as drivers of change. The case of ASD, we conclude, reveals that technology-led agroecological transitions will have difficulty succeeding unless they are embedded in broader efforts to transform the social and political relationships of industrial agriculture.

KEYWORDS
Agroecological transitions; anaerobic soil disinfestation; soil-borne pathogens; fumigant alternatives in strawberry production; SDG 12: responsible consumption and production

Introduction

Industrial agriculture, characterized by the intense use of fossil-fuel derived inputs, is a significant direct driver of global environmental decline with major

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social costs (Díaz et al. 2019). In contrast, agroecology as a science, practice and social movement, advocates for the integration of ecological principles in the design and management of agricultural systems (Altieri 2002; Gliessman 2020; Nicholls and Altieri 2018), with potential social and environmental benefits (Gliessman, Friedmann, and Howard 2019; Patel 2009; Rosset and Altieri 2017). But how can production systems currently dominated by industrial agriculture shift toward agroecology? While a considerable number of studies have documented the dissemination of agroecological knowledge and practices within regions dominated by small-scale farming (Ong and Liao 2020), much less research has examined how agroecology might take hold in contexts where agriculture is dominated by high-input, market-oriented monocultures, in countries with concentrated land ownership, industry consolidation, and where policy-making institutions have been captured by industry interests (Iles 2020; Tittonell et al. 2020). If agroecology is to take hold in the intensively farmed fields of the global north, we need a nuanced understanding of the socioeconomic, political, and cultural factors that entrench the industrial mode of food, as well as the enabling factors that make agroecological change possible (Anderson et al. 2019).

A variety of approaches within agroecology have emerged to understand, study and promote the dissemination of agroecological knowledge from local to landscape scales and throughout the entire food system (Montenegro de Wit 2021). This broadening of agroecology's reach is referred to variously (and with different implications) as "scaling up," "scaling out," "agroecological scaling," "massification," and "amplification" (Anderson et al. 2020; Hans et al. 2020; Mier y Terán Giménez Cacho et al. 2018). Scholars of agroecology propose two general frameworks for achieving this broadening of agroecology: agroecological transitions and agroecological transformations[1]. Agroecological transitions refers to the process through which farmers shift from low-diversity, high-input agriculture to a system that uses agroecological practices and relations (Blesh and Wolf 2014; DeLonge, Miles, and Carlisle 2016; Wezel et al. 2020). With roots in the sustainability transitions literature, this framework is primarily concerned with technological change and the social structures that make it possible, emphasizing the shift from one socio-technical regime or dynamic equilibrium to another (Geels and Schot 2007). Agroecological transformations, meanwhile, calls for more radical changes to social, economic and political structures (Anderson et al. 2019; Hölscher, Wittmayer, and Loorbach 2018). Agroecology, scholarship in this vein contends, is inseparable from the pursuit of social justice within food systems (Hölscher, Wittmayer, and Loorbach 2018; Patterson et al. 2017), as well as changes that move systems toward greater equity and sustainability (Petersen-Rockney et al. 2021; Raworth 2014). Agroecology as a radically transformative paradigm seeks to dismantle exploitative agricultural models through land reparations and land reform, and horizontal learning (Montenegro de Wit 2021).

Although agroecological transitions and transformations may seem to represent two opposite sides of the spectrum, they are not mutually exclusive[1],[2]. As Hölscher, Wittmayer, and Loorbach (2018) point: "both concepts provide nuanced perspectives on how to describe, interpret and support desirable radical, and non-linear societal change" (Hölscher, Wittmayer, and Loorbach 2018). Hölscher et al.'s review on the differences between transformation and transitions suggests that the two approaches and perspectives can enrich each other (Hölscher, Wittmayer, and Loorbach 2018). For instance, the concern that the transitions concept might encourage narrower interpretations of system change that do not challenge established power dynamics can be mitigated by evaluating and proposing agroecological transitions within the context of broader-scale transformations, encompassing aspects such as ecology, justice, and politics (Hölscher, Wittmayer, and Loorbach 2018). Similarly, transformation can emerge from incremental progress along context-specific transition pathways, building on a continuity of processes across knowledges, strategies, practices, policies and technologies, that alter farming systems (Petersen-Rockney et al. 2021). This article adopts just such a "both/and" perspective: we view agroecology as a transformative paradigm requiring deep engagement with the politics of our food system, but we also believe that a focus on concrete technical and ecological issues can form an important component of such transformative change.

Our analysis further draws from Anderson et al.'s (Anderson et al. 2019) concept of "domains of transformation" within agroecology (Anderson et al. 2019). This concept engages with Geel's et al.'s multi-level perspective (MLP) (Geels 2011, 2019) approach, offering a critical reformation based on the role of governance. MLP "views transitions as non-linear processes that result from the interplay of developments at three analytical levels" (Geels 2011): a) *niches*, the spaces where radical innovations arise and are incubated, b) the *socio-technical regime*, the established practices and dominant technologies that stabilize an existing system; and c) the exogenous *socio-technical landscape*, which forms a backdrop to the regime, containing and exerting pressure on the existing system (Geels 2011, 2019; Geels and Schot 2007). However, the MLP perspective has received significant criticism because it fails to address unequal power dynamics (Anderson et al. 2019; Geels 2011). As a response, Anderson et al (Anderson et al. 2019). further revised this framework to examine the fundamental role of governance for agroecological transformations by suggesting six critical "domains of transformation," which they define as "the discrete (yet interrelated) arenas where niche and regime meet, engage in conflict and mutual contestation, and where agroecology – through transformations in governance – can gain strength over regime-driven approaches" (Anderson et al. 2019). These domains[2] contain dynamics that are enabling (i.e. "drivers" of

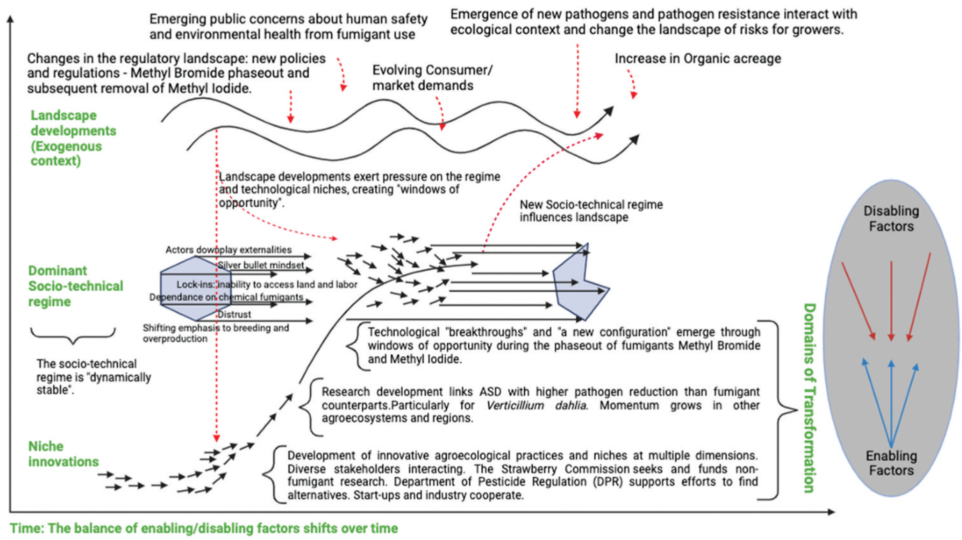

Figure 1. Agroecological transitions and adoption of ASD in California's strawberry landscape. On the left, the multi-level perspective (MLP) model shows three levels of transition: a) The dominant socio-technical regime: "the locus of established practices and associated rules that stabilize an existing system" (Geels 2011). The regime is locked-in by actors downplaying externalities, silver-bullet mind-set, high dependence to fumigants, distrust, and a shifting focus on productivity. b) Niche innovations (bottom), indicate the space where radical agroecological innovations take place. Innovations are developed and carried out by small networks of agroecologically-minded scientists, extensionists, farmers and a diverse sector of the industry. The development and adoption of radical innovations is also influenced by c) Landscape developments or the exogenous context (top), such as public pressure, momentum for agroecological transformation, and changes in the regulatory landscape, which exert pressure on the regime and technological niches, creating "windows of opportunity" and momentum (shown in red dotted arrows) for new innovations to take place and disrupt the dominant regime. domains of transformation: "the interface between niche and regime" (Anderson et al. 2020), constitute factors, dynamics, structures and processes that constrain agroecology (red arrows) and those that enable it (blue arrows), including policy changes, technological breakthroughs, and increased funding for research. Finally, the balance of enabling/disabling factors of transition is always dynamic and shifts over time, indicated in the time axis at the bottom of the model. The original MLP Model was developed by Geels and schot (Geels and Schot 2007) and revised by (Anderson et al. 2019) to include bottom-up governance as a critical domain of transformation(Anderson et al. 2020).

agroecology) as well as those that are disabling (i.e. "lock-ins" that obstruct agroecological processes).

Using the "domains of transformation" framework (Anderson et al. 2019, 2020) (Figure 1), this paper examines possibilities for agroecological transition in California strawberry production, a high-value specialty enterprise that relies heavily on chemicals (Guthman 2019). We analyze the challenges of adopting and maintaining ecologically-based alternatives to soil fumigation, with a particular focus on Anaerobic Soil Disinfestation (ASD) – an ecological and systems-based alternative to fumigation. Despite its promise, and early adoption primarily by organic growers in California, ASD has struggled to gain ground over dominant fumigant-based approaches. As a case study, the struggle to promote ASD adoption within the California strawberry industry illustrates the profound challenges of promoting agroecological transitions (not to mention transformations) within industrial agricultural regions in the global north, but also some openings for systemic change.

Specifically, we ask 1) What are the socioeconomic and ecological lock-ins facing strawberry growers in California? 2) What are potential drivers of change? and 3) What can this specific case tell us about the possibilities for agroecological transformations more broadly?

While focused on efforts to advance a particular agroecological practice within a very specific region and industry, our case underscores the need for transformative social change. We identify three primary disabling conditions for agroecological transitions- insecure land tenure and unequal land access; unequal systems of exchange (specifically unequal and unstable labor markets), and a culture that prioritizes hierarchical knowledge transfer and silver-bullet narratives. We argue that existing industry relationships that favor large-scale agriculture, rising costs and scarcity of land and labor, lack of transitional land policies, and silver bullet rhetoric make it extremely challenging for agroecological farming practices to gain ground and ultimately "lock-in" the dominant regime (Figure 1). In response to these challenges, we propose greater emphasis on initiatives that can support land access for small and medium-size growers who are at higher risk of disappearing; reshaping immigration law and immigration programs to allow for a more just and stable labor markets that benefit small and medium scale farmers; and reexamining extension mechanisms that currently favor top-down technocratic approaches. Collectively, our findings suggest that more robust support to transition to non-fumigant alternatives is needed, but that these changes need to urgently include broader social-political change.

Background: California's strawberry industry and fumigant alternatives

The California Coast is a major producer of strawberries, but has developed an increasingly complicated relationship with soil-borne pathogens such as Verticillium wilt (*Verticillium dahliae*), Fusarium wilt (*Fusarium oxysporum* . sp. *fragariae*), and Charcoal rot (*Macrophomina phaseolina*). The industry used to rely heavily on methyl bromide for fumigation (Daugovish et al. 2021a; Guthman 2019; Guthman and Zurawski 2020; Holmes, Mansouripour, and Hewavitharana 2020; Samtani et al. 2019), but it was phased out in 2016. Despite alternative methods being proposed (including fumigants such as Chloropicrin and 1,3-D), about 85% of California's strawberry fields still depend on soil fumigation (Daugovish et al. 2021a; Guthman and Brown 2016; Holmes, Mansouripour, and Hewavitharana 2020).

Anaerobic Soil Disinfestation (ASD) is an alternative to fumigation used in a variety of crops and to manage a wide range of pests, weeds and diseases (Blok et al. 2000; Shennan et al. 2014b; Muramoto et al. 2014; Lopes et al. 2022; Mazzola, Muramoto, and Shennan 2018; Shennan et al. 2016; Zavatta et al. 2021), gaining global popularity (Khadka et al. 2020; Shennan et al. 2014b; Priyashantha and Attanayake 2021; Rosskopf et al. 2020; Shennan et al. 2018; Vecchia et al. 2020). The method creates an anaerobic soil environment before planting, by adding a carbon source to the soil such as wheat bran, molasses, rice straw, or rice bran to promote microbial growth and respiration, followed by plastic tarping and irrigation (Momma 2008; Shennan et al. 2018). This process can take between 2–6 weeks, leading to the accumulation of disease suppressive compounds, as well as inducing changes in community composition and metabolic activity (Hewavitharana et al. 2019), which regulate soil-borne pathogens (Mazzola, Muramoto, and Shennan 2018; Shennan et al. 2014a). Combining ASD with other agroecological practices provides the best disease management results (Muramoto et al. 2022; Rosskopf et al. 2015; Shennan et al. 2018; Vecchia et al. 2020; Zavatta et al. 2021). Studies indicate that its effects last beyond the first cropping season, thus contributing to its ability to suppress disease in the longer term, particularly for *V. dahliae* (Rosskopf et al. 2015; Zavatta et al. 2021).

The strawberry industry in California was an early adopter of ASD in 2011, which saw rapid uptake from a limited number of growers, support from industry groups like the California Strawberry Commission, as well as the Department of Pesticide Regulation (Figure 2). The initial adoption of ASD was driven by public criticism of fumigant use, particularly the phaseout of MeBr (Guthman 2016a, 2016b), and a growing interest in organic agriculture. During this phase, the primary pathogen of concern was *Verticilium dahlia* (Lloyd and Gordon 2016). ASD proved highly effective in controlling this pathogen without significant changes to the initial fumigation system (Shennan et al. 2016). Positive results, coupled with the diminished effectiveness of Chloropicrin alone against *V. dahlia* without its potent enhancer MeBr, along with public sentiment and increased regulatory pressures at the time, led to significant ASD adoption in the first 5 years of its introduction (Muramoto, unpublished data).

However, the emergence of new pathogens, *Fusarium oxysporum* f. sp. *fragariae* and *Macrophomina phaseolina*, along with changing economic and labor dynamics in California, prompted growers to reassess priorities. These pathogens were less controllable through ASD in its current form, increasing the risk of adoption for growers, necessitating adaptations of the practice such

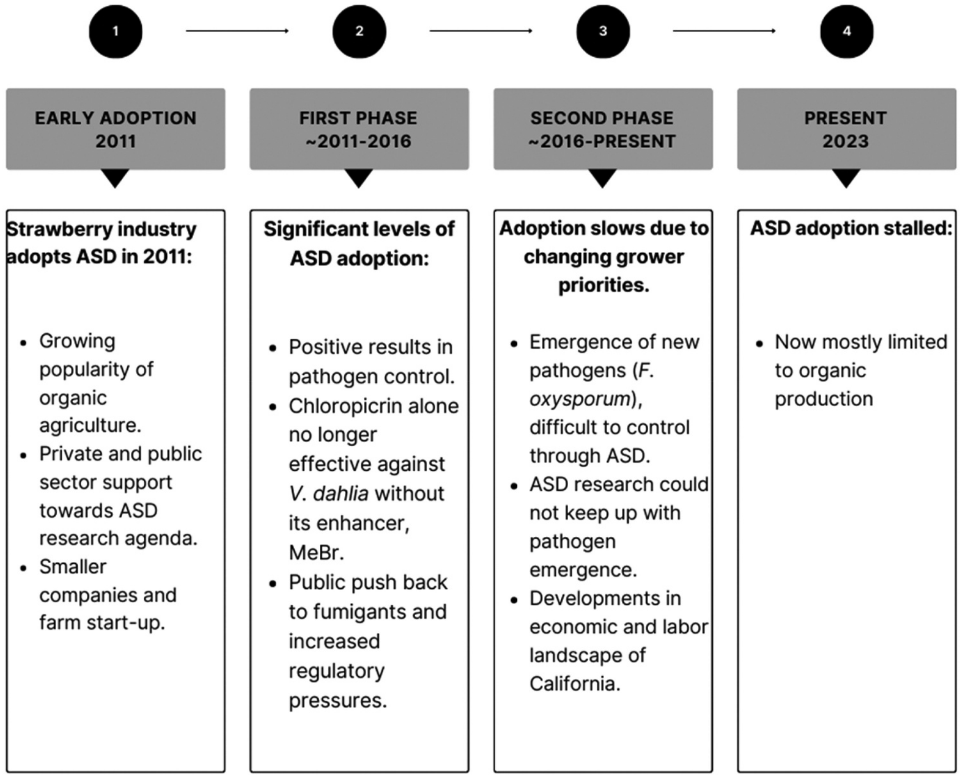

Figure 2. Shifts and balances in the adoption of Anaerobic Soil Disinfestation in California's strawberry landscape. A historical timeline of ASD adoption from 2011 to 2023. Technical issues comprise only part of the explanation for ASD's low adoption. Social factors play at least an equal role in shaping the conditions of possibility for ASD adoption.

as crop rotation for Fusarium's distinct life cycle(J Muramoto et al. 2014, 2015), and potentially the use of a resistant cultivar.

Technical challenges only partially account for the low adoption of ASD; social factors, equally significant, shape the conditions for ASD adoption. Our research delves into the social, ecological, and economic drivers, highlighting that many of these factors reflect food system inequality broadly, rather than technical problems with ASD alone (Figure 1).

Materials and methods

We carried out semi-structured interviews with 19 strawberry growers (6 organic, 6 conventional and 7 growers who practiced both organic and conventional) across six cities in the state of California (Monterey, Salinas, Watsonville, Santa Cruz, Oxnard, and Santa Maria). An initial list of grower participants was randomly selected from public records available at Agricultural Commissioners' offices, after which we selected further participants through snowball sampling until reaching saturation (Francis et al. 2010). We further interviewed 21 industry stakeholders working in extension, policy, and research. These participants were purposively sampled for their high degree of knowledge or influence about strawberry industry dynamics.

Our grower participants represented a diverse cross-section of small and medium-sized California strawberry growers. Farm size ranged from 4 to 300 acres. The smaller growers usually participated in smaller, more direct marketing channels such as farm stands, farmers' markets, and restaurants; the larger growers usually worked directly with major grower-shippers such as Driscoll's and Naturipe to access large, national and international retailers. As is common in California, most growers interviewed rented land, while a small minority grew a portion of their strawberry crop on land owned by their families. The growers we interviewed were heterogeneous in terms of their visions of production, their agricultural backgrounds, farming experiences, and education. For instance, some growers had an agronomy degree from Mexico, others received formal agricultural training in the US through agriculture apprenticeship programs such as Agriculture and Land-Based Training Association (ALBA). We interviewed growers that were about to retire, and others who had only recently made the transition to strawberry production or taken over a parent's operation. Some farmers identified as Latinx, others as white American and others as Japanese-American.

Our research protocol was approved by the Institutional Review Board (IRB) at the University of California Santa Cruz. To protect grower's identities, we refer to them using pseudonyms. Most interviews took place in person during 2019, though some were carried out over the phone during the COVID-19 pandemic beginning in 2020. Interviews were later transcribed and coded using qualitative data analysis software. This research is part of a USDA-funded Specialty Crop Research Initiative grant (SCRI), which investigates the potential of integrating ASD, crop rotations and disease-tolerant varieties to manage soil-borne diseases in strawberry production. Interviews covered experiences with and perceptions of ASD but also extended well beyond this topic to views on other agroecological practices, such as crop rotations, and conditions in the strawberry industry generally.

Disabling conditions for agroecological transitions in California's strawberry industry

In the Spring of 2019, Estelí Jiménez-Soto visited a 300-acre organic berry operation in California's Salinas Valley. The owner, Ernesto, knew his operational accounting with millimetric precision and – as Estelí jotted rapid notes – he rattled off the many costs associated with strawberry production: labor, water, rent, electricity, inputs, regulations. His account reflected the daunting task of administering and coordinating a successful berry business – a task that, in recent years, has become increasingly expensive and economically unsustainable for many growers. This interview, in fact, took place against the backdrop of an abandoned strawberry field. Like many other US growers, Don Ernesto had recently moved his strawberry operations to Mexico, a powerful market competitor. Around him, dead strawberry plants and tattered tarp held onto the dry soil as if these inseparable companions resisted leaving the valley. But as Ernesto explained, it was increasingly impossible to stay: "to be successful you have to leave for Mexico or wait until other farmers go bankrupt . . . there is just too much overproduction." The economic challenge of saturated markets is compounded by the agricultural challenge of keeping soils disease-free. During the interview, the grower described the extreme difficulties of managing pathogens and implementing crop rotations under conditions of low land availability, high land and labor costs, and increasingly diseased soils.

This general feeling of economic uncertainty and market hostility was shared by the smaller growers we interviewed. Mario, for instance, who grows strawberries with his dad on less than 25 acres in Watsonville, acknowledged the economic struggles facing small strawberry growers:

> We have lost year after year . . . And we have to front the cost of pesticides, gasoline, everything, even state trainings . . . it's nice to look at your plant and pick the strawberry . . . but I don't know what that money is for, because you hardly get anything . . . maybe, the big companies are going to survive, but the small ranchers, like ourselves . . . many of us are not going to survive.

In recent years, the California strawberry industry has faced increased environmental and biological pressure from droughts and the emergence of novel soil-borne diseases. These ecological challenges converge with a socio-economic landscape that benefits large-scale industrial agriculture. High rents, short-term leases, intense land competition, high production costs, and strict environmental regulations implemented without attendant support in transitioning to non-fumigant alternatives. This challenging environment limits the options for larger scale adoption of agroecological farming practices. More specifically, three disabling conditions for agroecological transitions in California strawberry production are identified: 1) insecure land tenure and unequal access to land, 2) unequal systems of exchange (particularly unequal and unstable labor markets), and 3) a knowledge culture which privileges silver bullet solutions and lacks horizontal knowledge exchange networks robust enough to counter them. Our interviews reveal how these factors stymie the adoption of agroecological farming practices such as ASD, locking in the current regime of chemical-intensive strawberry production.

Disabling condition 1: land tenure insecurity and unequal access to land

Achieving agroecological transitions locally, as well as broader food system resilience, requires urgent attention to land tenure systems (Calo et al. 2021). The cost and availability of land are well documented obstacles in the conversion to more sustainable farming systems (Calo et al. 2021; Carolan 2005; Lawry et al. 2017; Risgaard, Frederiksen, and Kaltoft 2007; Rosset and Martínez-Torres 2012; Rosset et al. 2011), including for California farmers (Carlisle et al. 2022; Guthman 2017a, 2019). Access to natural ecosystems, including land, is an important domain of transformation with the potential to enable changes in the current agriculture regime (Anderson et al. 2019).

California's unique climate conditions make it highly productive for agriculture, but also desirable for development. Accessing land to grow strawberries has become a major concern for growers due to limited land and increasing development pressure. High rents[3] directly fuel the intensification of strawberry production, including the use of fumigants, to maximize production and minimize crop loss to pathogens (Guthman 2017a).

Like other agroecological practices, ASD is difficult to carry out in the absence of stable and equitable land tenure. Ecological research suggests that crop rotations should optimally be 3–4 years for the effective management of soil borne diseases in strawberry production (Muramoto et al. 2014). However, the high cost of land makes longer crop rotations with non-host crops difficult (Holmes, Mansouripour, and Hewavitharana 2020; Njoroge et al. 2009; Zavatta et al. 2021). For instance, *F. oxysporum* f. sp. *fragariae* is specific to strawberries and can only be rotated with a few crops. In contrast, *V. dahlia* can be hosted by over 400 plant species, making it challenging to avoid host crops during rotations. However, low access to long-term leases along with high land costs makes healthy rotations virtually impossible, as one grower put it: "if you find land that you can rotate three consecutive years with a crop that will not regenerate Fusarium, congratulations . . . there is no plots to do this type of healthy rotations. This is the biggest obstacle I see: there is no land to make a healthy rotation and minimize disease inoculum." An extensionist noted that growers renting land lack both the incentive and the capacity to manage for soil health:

> I mean, it's not that [growers] don't care, it's just that they almost don't have the bandwidth to be able to care . . . they have to hurry up and get it all done, they have to max out so that they can make money, and then they don't know if they're there or not the next time. It's just like they just are going as fast as they can.

Growers we interviewed noted that non-host crops required for rotation, such as broccoli, were not profitable enough to justify the high land rents, which are based on the potential profit from strawberries in a given piece of land (Guthman 2019). For instance, during a field visit in Watsonville, a grower pointed at his cousin's neighboring broccoli field indicating that the return would be so little that harvesting the broccoli did not make economic sense. Short-term leases and high rents make it difficult for growers to justify dedicating time and resources to carry out rotations or ASD, as their ecological advantages would likely not benefit growers in the short-term (Dula 2017).

Land access is also tightly linked with farmers' local knowledge. Hence agroecological movements have strongly emphasized land reparations and reform as the basis to reclaim food sovereignty (Calo et al. 2021; Montenegro de Wit 2021). Growers with unstable access to long-term leases may lack the necessary place-based knowledge of fields and microclimates to effectively conduct agroecological practices, which must be adapted to local conditions, such as soil microbiota (Vecchia et al. 2020), existing pathogens (Muramoto et al. 2016), local temperatures (Zavatta et al. 2021), and soil type (Runia et al. 2014). This intricate relationship between land and knowledge makes agroecology highly context dependent. Yet, growers held differing perspectives on whether land access alone was sufficient to allow them to pursue agroecological methods. Some growers, for instance, argued that – regardless of whether you own or rent – success within the strawberry industry is dependent on maintaining high yields, which is difficult without the use of fumigants.

To manage land cost and access, growers often associate with shipper companies, who provide a host of services to their affiliated growers, including bringing the fruit to market, providing technical assistance to growers through their own Pest Control Advisors (PCA), and providing plant varietals through their own breeding programs. Shippers can help farmers find suitable rotation partners – growers who can farm the same fields in alternate years – whose crops will not exacerbate disease problems. One shipper representative we interviewed argued that shippers are also now facilitating better land management by offering growers longer leases than had been possible historically, allowing for long term management and grower operating cost budgeting. However, some smaller growers (less than 50 acres) provided a contrasting vision, arguing that shipper companies are contributing to land access problems for smaller growers: "the shippers are grabbing almost all the land. All the land is for their own growers. And for small farmers, land is hard to come by."

Collectively, land struggles – increasing land costs, short-term leases, competition for scarce land, increasing acreage, and associated debt – contribute to the inability of strawberry growers to adopt agroecological practices, such as ASD and crop rotations. Paradoxically, in this highly consolidated and industrialized production regime, stable land access and the possibilities for more sustainable production it entails, are – for many growers – only attainable through association with the dominant corporate model. This is a catch-22 for agroecological transitions, which prioritize both sustainable production and farmer autonomy from corporate control (Niederle et al. 2022).

Disabling condition 2: Unequal systems of exchange: Labor scarcity and the cost-price squeeze among farmers

California strawberry growers find themselves in a "cost-price squeeze," caught between increasing input and labor costs on the one hand and stagnant crop prices on the other (Guptill and Welsh 2008; Lyson, Stevenson, and Welsh 2008). These challenging farm economics place farmers on a "treadmill of production" (Cochran 1993), an endless cycle of overproduction and indebtedness which makes it very difficult to adopt more sustainable farming practices (Bell 2010).

The high cost of scarce labor poses significant challenges for California strawberry growers, especially during the labor-intensive harvest season (Carlisle et al. 2022; Holmes 2013; Rutledge and Taylor 2019). Labor shortages have been driven by a variety of factors, including increasingly punitive immigration[4] regulations (Calavita 1989; Davila, Pagan, and Grau 1998), changing demographics, and a shift in opportunities and desires for younger generations in Mexico and the US (Rutledge and Taylor 2019). The H-2A program provides a temporary solution, but it comes with significant cost and bureaucratic hurdles that are particularly challenging for small to mid-scale growers[5].

The scarcity and expense of labor, limits possibilities for adopting agroecological practices. A strawberry grower explained how the high cost of labor is tightly linked to management decisions that lock-in industrial agriculture: "I mean, in 2022, we are going to have a minimum wage of $15, and a workday of 40 hours, this completely puts agriculture against the wall . . . and the market has not kept up with that. Now we have varieties that produce more, and there are new fertilizers, and more technology. Yes, we are producing more per acre now, and that has kept us going." Ever-higher labor costs fuel the production treadmill, leaving growers with little choice beyond intensification, which only accelerates a multilayered social and environmental crises.

Labor shortages can be particularly damaging for diversified and organic growers who rely on manual labor for the control of weeds. An extensionist we interviewed explained that labor requirements are simply higher for organic growers: "If they want to go organic, there's no good herbicide to control weeds, which means it costs more for manual labor, and the labor shortage can be a hindrance. I can speculate that growers who want to try to shift to organic may have a bit of hesitation too because of that." The lower yields associated with organic production may also be a challenge for recruiting workers. Because wages are generally based on a piece rate system in which pay corresponds to volume harvested, laborers can make more money harvesting the larger fruits of conventional agriculture (Soper 2020a, 2020b). An organic grower explained: “I do have labor challenges because you don’t pick as big a crop as a conventional field. So, workers aren’t attracted to the organic field. So, you end up having to pay a little more to try and keep workers . . . .”

In addition to high labor costs, strawberries require many other costly inputs which demand a high up-front investment and starkly limit management flexibility. As Estelí talked to Ernesto, the list kept growing: food safety costs, office expenses, pre-plant inputs, sprinkler irrigation, tarp costs, trays and clamshells, etc. An extensionist explained: “growers are pretty much dealing with the large investments they put upfront with a berry crop. They are just a price-taker basically.” Another industry stakeholder explained that this cost-price squeeze meant growers could not prioritize soil health: “the reality is that those guys are trying to beat the market and the price point; they actually don’t even necessarily care if there’s disease in the field. As long as those berries were bigger, they filled more boxes, they managed to get it out of the field when the price was good, they kind of don’t care if there’s some disease in the field.” With significant up-front costs, growers are compelled to engage in intensive production or risk going out of business.

Their high production costs and subordinate market position limit grower ability to risk experimentation with agroecological practices such as ASD. A stakeholder in extension and education explained that ASD – though potentially economically competitive with fumigants – can involve hidden costs for growers:

> We’ve never had a farmer pursue ASD on their own. Cost is one [reason] . . . Not just financial, investment of money, but also opportunity cost. It’s a big planning process with ASD where you’re getting your beds ready a lot earlier, getting plastic up earlier. And that’s all time you can have another crop growing.

One grower we interviewed had recently stopped using ASD, despite positive experiences, because it was just too expensive on top of high labor costs and other inputs:

> . . . 2018 was so bad. We lost so much money. The last two years, we’ve had to seek and get a loan just to pay the people. So, I owe money out to the lender. So, okay. Last year we didn’t do the ASD because ASD is, to me, an expensive practice. It’s around $3,000 an acre. Just for the rice bran, and then you’re doing the other practices and things like that. Which I normally do, but the rice bran is expensive. So, I dropped back, pulled my horns back a little bit and just did drip fumigation, which is putting the beds up, drip in, covering it with plastic, and then putting Telone, chloropicrin in through the drip . . . So I saved money there.”

In the face of ever-increasing labor costs, this grower was forced to abandon ASD for the lower-cost fumigation option.

Further, the inputs required to practice ASD are also becoming more costly and challenging to source. In recent years, rice bran – a byproduct of rice processing and one of the most common Carbon sources for ASD – has become increasingly expensive and, given its increasing demand from animal feed industries overseas, difficult to source. For this reason, rice bran has become increasingly costly, often surpassing the cost of fumigation, making ASD less attractive as an alternative to fumigants: "rice bran is very expensive ... and then you are not always guaranteed that it will be delivered on time ... We have many budget limitations. We must be careful with our investments." In an effort to diversify Carbon sources, studies are starting to test locally sourced organic materials, such as crop and cover crop residues, mustard seed meal, corn gluten, coffee grounds, brewery waste, wheat mill-feed, and citrus and beet molasses as an alternative to rice bran (Daugovish et al. 2021b).

Together, the costs of labor and alternative inputs make it difficult for growers to maintain agroecological practices while staying within sustainable economic margins. Growers are embedded within systems of exchange which force them to accept high costs of inputs and low prices for their produce. This gives them very little flexibility and locks them into using fumigants and focusing on short-term solutions to soil-borne disease.

Disabling condition 3: Silver-bullet rhetoric, a weakened system of social networks and technical knowledge gaps

Knowledge and culture, a third domain where regime transformation can occur (Anderson et al. 2019), refers to the mechanisms by which agroecological knowledge is constructed and shared, as well as the cultural practices and discourses engrained in the agrarian cultures of place that have the capacity to hinder or mobilize agroecology at larger scales (Anderson et al. 2019). Agroecological practices are developed through robust social networks, and the degree of social organization for knowledge exchange can determine the scalability of agroecology (Anderson et al. 2019, 2020; Mier y Terán Giménez Cacho et al. 2018; Pimbert 2017). In the case of the strawberry industrial complex in California, the knowledge-intensive nature of ASD interacts with a solidified silver bullet approach to disease management, and a weakened system of social networks that is dominated by top-down extension mechanisms, resulting in the limited scalability of agroecological approaches.

On a cool January morning in Salinas, CA, as the rumors of Coronavirus cases began to emerge across the globe, the University of California Cooperative Extension (UCCE) hosted their annual research and extension meeting for strawberry growers in an event room within the Salinas Rodeo.

The event attracted a large group of strawberry growers from across the Central Valley, whose *trokas* (pickup trucks), still dusty from the fields of Watsonville and the Salinas Valley packed the parking lot. Upon entering the room, attendees picked up a program listing the various research updates that would be presented by extensionists and researchers, many with highly academic titles: "A Systems Approach to Manage Fusarium in Both Organic And Conventional Fields," "Biology and Epidemiology of Leaf Blotch Caused by Zythia in Strawberry," and "Accuracy of Genomic Selection for Resistance to Verticillium Wilt in a Strawberry Population Spanning 165 Years of Breeding." These titles were just the first glimpse at the immense communication divide felt between the extensionists at the podium and the community of growers sitting below. Presentations showed complex phylogenetic graphs and were filled with statistical language and genetics jargon. Research on ASD and other non-fumigant approaches followed the same top-down extension style. When the meeting ended, Estelí approached a group of Hispanic growers who were gathered by the entrance and who, when asked their thoughts on the event, did not hesitate to express that the presentations felt inaccessible and far removed from their reality. They came to these events, they explained, just to meet and exchange ideas with other growers. This informal and horizontal exchange of information was where the true value of the meeting lay for them. The experience at the rodeo underscored the pressing necessity to rethink the cultures of communication and knowledge-sharing that reinforce the divide between farmers and extension and research personnel, which further impedes transformation.

In stark contrast to fumigation, agroecological practices that increase soil quality (such as rotations) and a focus on soil microbial diversity require complex ecological knowledge and agronomic flexibility. The result of ASD depends on the grower's ability to adjust to environmental and biotic conditions, and adapt farm technology, while also conducting scientifically-sound and place-based research to respond to new challenges. The experience with ASD over the years has shown that scientific knowledge gaps remain that limit fully support agroecological transitions under new global scenarios. The emergence of potentially devastating pathogens, as demonstrated by the rapid transition from *Verticillium* to *Fusarium* and *Macrophomina*, coupled with the dynamic shifts in climate conditions, highlight the ongoing need for research in microbial ecology, agronomy, plant pathology, and soil science. Although farmers that use fumigation also manage soil characteristics (pH, temperature, and soil texture), the intensity of these activities is even greater for ASD (Holmes, Mansouripour, and Hewavitharana 2020). For instance, adjusting the timing to reach anaerobicity is based on local climatic and soil conditions, which interacts with farmer-specific production goals, infrastructure available, and – potentially – the existing soil microbial community.

In addition, the heavy reliance on fumigants that characterized the Methyl Bromide era left a legacy of dependence on "silver bullet" chemical pest management, and top-down extension and knowledge transfer. These dynamics are deepened and perpetuated by a productivist rationale that pressures farmers to maximize yield, and leaves little room for experimentation. While farmers find some benefits from extension events like the one described above – such as connecting with other farmers – the hierarchical structure of knowledge sharing and innovation in California's strawberry landscape, mostly represented by university extension and large companies, is widespread and has disrupted social networks. This presents new entry and small-scale farmers (many of whom are Hispanic in California) with limited access and participation.

The industrial complex has also led to the concentration of input supply channels in the hands of a few actors – primarily private agro-industrial companies. In the early years of ASD adoption in California in 2011 (Figure 1), local and small companies that sourced rice bran for growers would also provide technical assistance and monitoring post-application. Independent suppliers such as FarmFuel Inc. provided essential support to the growers who purchased from them. However, as ASD began to gain a foothold, the market for rice bran was overtaken by agrochemical companies that also distribute fumigants but offer little to no technical assistance on soil processes critical for ASD. Smaller research and farmer-oriented businesses can provide growers with technical assistance, but they may lose to competition from major agrochemical providers which act as a one-stop-shop for farmers, as highlighted by one of the founders of a farmer-oriented start-up:

> They've got boots on the ground and what they do is say well hey you're going to do bran this year I'll get it for you, no big deal I'll get it for you, I'll sell it to you for less. And what they do is they find out what I'm selling it for, and they sell just underneath me. And [the agrochemical companies who sell rice bran] are not making sure they are doing it right . . . so now it has moved from ASD as a tool to either replace fumigants and to treat organic ground, to rice bran being part of the soil input program . . .

The experience highlighted by this farmer-oriented start-up representative, underscores a broader issue related to the prevailing extension model which often fails small growers and those from minority backgrounds. Furthermore, when major agrochemical suppliers assume the main role of input supply, practices and knowledge such as ASD are reduced to yet another "antibiotic" approach, which is applied indiscriminately without attention to process, ultimately doing ASD and other agroecological practices a disservice (Guthman 2019).

To enable the mobilization of agroecology, education and extension processes require reflecting and understanding place-based complexity and farmers' lived knowledge and farmer culture. However, these processes do not necessarily happen in official institutions and networks (Anderson et al. 2020). The way in which knowledge is constructed and distributed in conventional network channels can prevent the successful scaling of agroecology because the process is usually de-contextualized, favoring goals and knowledge of dominant groups, who often have profit-led research agendas (Anderson et al. 2020; Velarde and Marasas 2017). Vertical knowledge transfer models have been extensively criticized because they do not favor the development and strengthening of farmers capacities and local knowledge (Velarde and Marasas 2017; Warner 2007).

Efforts to scale-up the use of non-fumigant approaches in California are hampered by this same hierarchical knowledge culture. We found that field days and extension events organized by the university extension system were instrumental in introducing growers to sustainable alternatives, yet the Latinx and Japanese-American growers felt very strongly that researchers were using highly technical language that was difficult to comprehend. The use of scientific jargon at these events creates a communication barrier and ultimately impedes the adoption of agroecological practices, especially given the familiarity, general applicability, and predictability of fumigants, which align well with silver bullet approaches. This poses a significant barrier for the adoption and dissemination of agroecological practices.

Opportunities for change within California's strawberry industry

While the existing socio-technical regime of California strawberry production includes major lock-ins that constrain agroecological approaches like ASD from scaling out, potential drivers of change exist within and outside the dominant regime. We briefly consider two: 1) the cultural and knowledge diversity of small and medium-size growers, and the institutions and networks that have arisen to support their needs; and 2) increased momentum for bottom-up transformation and regime change (Figure 1).

Opportunity for change 1: cultural diversity, knowledge, and support networks

Today, Latinx growers comprise almost two thirds of all strawberry growers in California (Wozniacka 2012), many of whom have rich agricultural backgrounds. Similarly, Japanese farmers that established in California's Pajaro Valley and Watsonville in the 1890's and early 1900's were pioneers in innovation for California's agriculture, growing diversified farming systems (Linda L. Ivey 2007). Our research within the California strawberry industry confirms that beginning farmers can be a positive transformative force for the future, along with more cooperative forms of farm organization, and farmer-led learning approaches that truly transform farming livelihoods, beyond skills-building programs (Doherty et al. 2023). We found value in activating and scaling up extension, education, and participation opportunities through apprenticeship programs that offer political education, are fully bilingual and college accredited, and offer creative and collective initiatives for equitable land access (Calo 2020; Calo and De Master 2016).

Focusing on the needs and challenges of small-scale, minority, and new entry farmers – in this case mostly Latinx growers who were once farmworkers – is critical because at present they are not adequately addressed by the dominant industrial regime and agricultural programs. Focusing on this sector may offer a promising avenue for advancing agroecological transformations because their farming experiences converge with larger challenges of our food system such as unequal access to land, racial injustices and economic discrimination, some of which were revealed in our study. Further, recent years have seen growing attention to small and mid-sized farms in the United States – both the immense challenges they face in attempting to stay afloat (Lyson, Stevenson, and Welsh 2008), and their potential to make unparalleled contributions to agroecological transformation of food production (Kirschenmann et al. 2008). Scholars have also emphasized that cultural diversity within this sector can be key to fostering environmental and social sustainability at larger scales (Minkoff-Zern 2019; Wezel et al. 2020).

Using an agroecological transitions lens to examine opportunities for change in the strawberry industry, exposed the importance of supporting educational programs such as ALBA's farmer-led programs. Yet, considering beginning farmers as a transformative force will require addressing the systemic inequality faced by marginalized communities in California's Central Valley and Central Coast areas, and the physical and mental stress farmers experience as a result of their participation in the industrial agricultural complex (Doherty et al. 2023). Supporting beginning BIPOC farmers also requires addressing unequal determinations of "credibility" for land acquisition and credit access that have been historically detrimental for this sector (Calo 2020; Calo et al. 2021).

Opportunity for change 2: momentum for agroecological transitions: social movements and political reform

Social movements and civil society organizations are at the forefront of positive change when it comes to pesticide use in the United States. In the U.S., some of the earliest and most enduring forms of political activism against pesticide exposure found their roots in farm labor organizing in California (Harrison 2011). These labor struggles were instrumental in shaping worker protections aimed at mitigating the hazards of agricultural pesticide exposure, which can be considered one of the earliest nationally recognized initiatives spearheaded by people of color to address environmental concerns (Nash 2004). Further, the emergence of alternative food movements and alternative agriculture has promoted the emergence of diversified farming systems, as well as the mechanisms, markets, and progressive institutions to support them (Carlisle et al. 2022).

We suggest that, in the context of the strawberry industry, popular movements and organized civil society will continue to be a transformational force in California, particularly 1) if regulatory bodies incorporate public demands for environmental justice issues into policy actions, and 2) if they implement better policies to support agroecological transitions (such as addressing land and labor constraints). This includes agricultural policy reform to increase funding to support transition to agroecology and sustainable food systems, particularly for small-scale BIPOC farmers (Carlisle and Miles 2013; DeLonge, Miles, and Carlisle 2016; Miles, DeLonge, and Carlisle 2017). Funding from the USDA should also distribute efforts more equitably, beyond projects that focus on tackling individual agronomic problems, and instead direct funding toward social-ecological research that facilitates a bridge between agroecological producers and consumers (Miles, DeLonge, and Carlisle 2017). Imposing *pesticide taxes* and utilizing this revenue to incentivize agroecology and agroecological farming practices could gradually promote the transition to agroecology, as well as disincentivizing pesticide use (Miles, DeLonge, and Carlisle 2017). Further, agriculture reform is needed to address the requirements for acquiring and maintaining farm insurance (Epstein 2014). For example, farmers often are required to follow "best management practices," which in many cases includes the use of pesticides, in order to collect indemnities from federally subsidized crop insurances (Epstein 2014; Horowitz and Lichtenberg 1993).

Excellent examples of organizations, popular movements, and collective efforts, toward agroecological transition in California include the Pesticide Action Network (PAN), which has crafted a report for Policy Makers calling for the establishment of measurable goals to reduce synthetic pesticide use in agriculture, promote the transition to diversified farming, and adopt regulations that support the rights of groups who are most impacted by fumigants and pesticides (Sharma, Reeves, and Washburn 2022); Californians for Pesticide Reform (CPR), and initiatives within the California Department of Pesticide Regulations, such as the Pesticide Use Reporting System (PUR).

While we agree that market-based solutions will not replace deeper systemic transformation to address increasing market concentration and overproduction, improving market access for small-scale diversified agroecological farmers, particularly during the transition, could be an opportunity to maintain sustainable farmers in business.

Discussion: toward an agroecological transformation

While research into agroecological transitions has tended to focus on smallholder agriculture, agroecological transitions are also urgently needed within landscapes dominated by consolidated, industrial production. This paper has explored the possibilities for agroecological transition within one such industrial production regime: the California strawberry industry. California growers produce 90% of the strawberries consumed in the US, but this production is highly fumigant and pesticide intensive, resulting in serious social and environmental repercussions. This paper examined the challenges and opportunities for an agroecological transition within California strawberry production, focusing specifically on the adoption of Anaerobic Soil Disinfestation (ASD), a promising agroecological farming practice used in combination with crop rotations and diversification, which supports the regulation of soil-borne pathogens without toxic fumigants.

Our examination of ASD's adoption among California strawberry growers uncovered strong regime "lock-ins" (or disabling conditions) that block agroecological transitions and preserve the *status quo* of industrial agriculture, hampering broader agroecological transformation (Anderson et al. 2019). These included: unequal land access and insecure land tenure; the high cost of labor and other agricultural inputs; and a knowledge culture which privileges top-down, silver bullet solutions over horizontal knowledge exchange. These challenges force farmers to prioritize meeting financial obligations, over long-term sustainability goals, leaving little space for knowledge-intensive practices to gain traction against fumigation. We also identified potential "drivers of change" (or enabling conditions) that act as transformational forces for agroecological transition (Figure 1), including the deep agroecological knowledges held by small-scale, minority, and new entry farmers, and the political momentum building around stricter pesticide regulation (Carlisle et al. 2019, 2022).

Our research shows the paramount importance of land access and suggests the need for policy reform. Land access interacts with agroecological transformations in complex and contradictory ways, as in the case of large grower-shipper companies helping farmers obtain longer term leases. While these interventions address land access issues for farmers in the short term, they are usually only accessible for large-scale farmers and may therefore serve to intensify farm sector consolidation, as well as reinforcing corporate control within the food system. Robust legislation is urgently needed to ensure that farmland is accessible to farmers of all scales and over time periods that allow for agroecological production. Such legislation would include policies to limit the financialization of farmland (Carlisle et al. 2022; Fairbairn et al. 2021), such as the recent *Farmland For Farmers Act* (S.2583), which provides new tools for governing speculative land purchases by corporations. Such legislation would also address deep histories of racial injustice within agriculture, as in the case of the *Justice for Black Farmers Act*, which aims to repair some of the damage that discriminatory USDA practices inflicted on generations of Black farmers. Bills such as *Increasing Land Access, Security, and Opportunities Act* would also strengthen land, capital, and market access outcomes for historically underserved farmers and ranchers operating in high-poverty areas (Budzinski, 2023).

Our analysis also points to labor policy as another area of opportunity for agroecological transformation. Like other scholars, we find that unequal labor markets present major challenges for adopting agroecological farming practices (Graddy-Lovelace and Naylor 2021; Minkoff-Zern et al. 2022). In consequence, there is a need to rethink the H2A program, which currently benefits mostly large-scale operations and presents further economic burdens on medium and small-scale farmers who are already experiencing the cost price squeeze (Lyson, Stevenson, and Welsh 2008; Minkoff-Zern et al. 2022); to implement subsidies for moderate-sized producers to invest in stable labor forces and training programs that would allow farmworkers to achieve leadership roles in agriculture (Minkoff-Zern et al. 2022); and to enact equitable, sustainable and humane pathways to citizenship for new-entry farmers (Calo and De Master 2016; Minkoff-Zern et al. 2022).

Finally, while socioeconomic and political conditions of the broader landscape of production are important, addressing technical questions using theories and methods from ecology, soil sciences, agronomy, and plant pathology should by no means be overlooked. This is especially true for agroecological practices, which unlike fumigants and pesticides, are often sensitive to location-specific environmental factors, demanding a nuanced approach tailored to the intricate interplay of environmental and biotic factors. The technical challenges experienced during the sudden emergence of pathogens in California's strawberry fields emphasize the necessity of continuously expanding our understanding and knowledge base to effectively address evolving agricultural issues at all scales. This requires robust science programs, as well as ample collaboration across disciplines, extension agencies, and regions, and actively engaging with the technological and knowledge generation challenges that farmers and agroecologists encounter in their pursuit of sustainable practices. Consequently, the scaling-up of agroecological practices requires a departure from conventional research and extension methodologies. This may entail, on the one hand, a slower and more adaptive response to emergent stressors (Petersen-Rockney et al. 2021); and on the other hand, leveraging existing scalable opportunities for agroecological transitions, such as promoting the co-creation of knowledge, and strengthening bottom-up educational initiatives for small and new entry farmers, who are potential transformational forces for California's agricultural landscape.

In conclusion, our analysis underscores that technology-based agroecological transitions, must be paired with more transformative changes that address the root causes of environmental decline and facilitate socially sustainable production. Although our interviews focused largely on ASD and soil-borne disease, these rather technological and agronomic entry points quickly led us toward the broader structural challenges facing growers as they attempt to transition from fumigation to agroecological farming practices. Agroecology, as a transformative paradigm, necessitates the redesign of agriculture and food systems using ecological, social, and political principles to regenerate nature and promote a more just society. Our findings emphasize that the success of such transitions hinges on weaving individual technologies into a broader framework that addresses the structural challenges facing growers, transforming the social and political relationships inherent in industrial agriculture.

Notes

1. There is ample debate about how to define the "scalability" of agroecology and the terminology is an unresolved discussion. Yet, agroecological scaling or massification refers to a worldview in which relationships, processes, policy, power, and practice nurture social organization, learning, and adaptation (Ferguson et al. 2019).
2. The domains (Anderson et al., 2019) identify are: access to natural ecosystems; knowledge and culture; systems of exchange; networks; discourse; and gender and equity. It is important to note that each of the domains suggested is mostly determined by governance, rather than the technical aspects of sustainable transitions originally proposed by Geels et al. (2018) in the MLP framework of transitions (Geels, 2018).
3. During the time of data collection, rents of up to $3,000/acre were reported (Guthman, 2019).
4. The Immigration Reform and Control Act of 1986 (IRCA) (Calavita, 1989), heightened control at the southern border and created significant penalties for employers who hired illegal workers in the United States with the primary objective to reduce immigrant labor (Davila et al., 1998). More recently, labor shortages have also been driven by tightening immigration regulations during the Trump administration (Milkman, 2018), which increased border detentions of undocumented migrants, and threats to sanctuary cities, such as Watsonville, CA, California's prime strawberry producing town.
5. Growers have responded to increased labor costs in various ways. Some have relocated to Baja California where labor is cheaper and less regulated. Others have switched to less labor-intensive (though frequently more resource-intensive) crops, such as nuts or row crops (Rutledge and Taylor, 2019). The labor shortage has also increased attention of strawberry growers and extensionists to cultivar selection, including high yielding fruit, shelf life, flavor and size (Guthman, 2017b), although this has not solved the problems with soil-borne diseases, and has in fact intensified the treadmill in which many small and mid-size growers find themselves trapped (Guthman and Jiménez-Soto, 2021).

Acknowledgments

We are thankful for the generous time and insight provided by strawberry growers, field managers, farm advisors, extensionists, policy makers, and industry stakeholders in California. We thank members of the Agri-food Writing Group at the University of California Santa Cruz (UCSC) for their insightful comments in the early stages of writing: especially Emily Reisman, Julie Guthman and Maywa Montenegro. We also thank the research and general editing support provided by April Lopez, Graduate Research Assistant at Syracuse University and Diana Stone URA in Jimenez-Soto's lab. We also thank the reviewers who helped us improve the initial version of our manuscript. Research for this project was supported by a Specialty Crop Research Initiative grant from the United States Department of Agriculture # USDA-NIFA SCRI Program #2017-51181-26832.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Research for this project was supported by a Specialty Crop Research Initiative grant from the United States Department of Agriculture to C. Shennan # USDA-NIFA SCRI Program #2017-51181-26832.

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