Agriculture and Human Values
https://doi.org/10.1007/s10460-024-10615-x

Precision agriculture and the future of agrarian labor in the US food system

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Accepted: 10 July 2024

Abstract

Precision Agriculture (PA) uses sensors, drones, and machine learning algorithms to provide farmers with site-specific information for targeted farm management decisions. These technological systems can reconfigure farm labor, replacing or displacing agrarian workers, especially unskilled, seasonal, hired, and migrant labor. Therefore, PA raises critical social questions that have implications for farmers' autonomy and control over agrarian production systems. We critically examine the social consequences of PA through the theoretical lenses of accumulation by dispossession and the agrarian question of labor. We use data from six focus group discussions conducted during the Fall of 2019 in heterogeneous production systems in South Dakota and Vermont. We assert that agritech firms design PA technologies as accumulation strategies predicated on the dispossession of farmers' autonomy and control over agrarian production systems. As such, PA is fundamentally reconfiguring the future of agrarian labor in the US food system.

Keywords Precision agriculture · Accumulation by dispossession · Agrarian labor · Agrarian question of labor

Abbreviations

AGRITECH	Agricultural technology firms
FGD	Focus group discussion
PA	Precision agriculture
NGO	Non-governmental organization
US	United States
USDA	United States Department of Agriculture

Introduction

Precision agriculture (PA) is a collection of technologies that support farmers in making informed farm management decisions (Bongiovanni and Lowenberg-Deboer 2004; van der Burg et al. 2019; Posadas et al. 2023). Farmers are adopting PA technologies such as tractors capable of automatically steering and navigating on a farm, farm equipment fitted with sensors, and various data collected through satellites, weather stations, and drones that operate through machine learning algorithms. PA technologies can purportedly provide 'precise' farming recommendations to farmers about when to sow seeds, graze farm animals, and harvest crops (Coble et al. 2018; Ogunyiola and Gardezi 2022; Wolfert et al. 2017). Proponents of PA in the private and public sectors, such as agriculture technology firms (henceforth *agritech*), including John Deere, and state actors often frame PA as an innovative solution to address productivity gaps, resource depletion, and ecological degradation in agri-food systems (van der Burg et al. 2019). For instance, a United States Department of Agriculture (USDA) study revealed that many farmers who adopted PA increased their operating profits (Schimmelpfennig 2016). However, the economic costs of PA to smallholders and marginalized

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Published online: 21 August 2024

farmers within the increasingly globalized and concentrated agricultural sector remain understudied (Rotz et al. 2019a).

Against these promising claims of economic and environmental benefits, recent scholarship on 'digital agriculture,' 'precision agriculture,' and 'smart farming' emphasizes the socio-ethical implications of adopting PA (Gardezi et al. 2022a, 2022b; Ogunyiola 2021; Posadas et al. 2023). This strand of social science research has mainly focused on evaluating the economic and environmental outcomes of PA, changing social identities of farmers, and data ownership issues, with growing attention to how PA might transform different classes of agrarian labor while creating economic surplus for agritech (Bronson 2018; Carbonell 2016; Fraser 2019; Rotz et al. 2019a; Stock and Gardezi 2021).

Agritech's design of PA has broader implications for agrarian production systems and farm labor. For instance, the adoption of capital-intensive technologies in agriculture through the advancements in precision agriculture is transforming the agricultural production modes in the US. For example, 53% of corn and soybean farmers in South Dakota operate PA technologies on their farms (McFadden et al. 2023; Kolady et al. 2020). PA provides an alternative to traditional, labor-intensive farming methods. For instance, robotic milking systems, one of the earliest precision livestock technologies, have inbuilt sensors that measure the amount of milk and monitor the health of animals, providing critical detailed information during feeding and milking that reduces the amount of time farmers and farmworkers spend tendering for their livestock (Allen 2017; Egan 2015; Charles 2018).

As with other PA technologies, however, the adoption of robotic milking systems is rescripting and reconfiguring agrarian labor. Farmers are transitioning into 'digital laborers', relying on automation and data-driven approaches. This shift reduces the need for manual farm laborers and alters the role of farmers, emphasizing the importance of their expertise in managing these technologies (Eastwood et al. 2012; Klerkx et al. 2019; Ogunyiola and Gardezi 2022). Robots adopted by farmers can milk about 60 cows three times in 24 h, and cows can freely move or be guided to the robotic milking system rather than the traditional two times carried out by farm laborers (Charles 2018; Purdy 2016; Schewe and Stuart 2015). Machine-facilitated efficiencies in production systems can increase the profit margins and improve time efficiencies unevenly throughout the agricultural labor force, with most benefits accruing to farm owners with enough financial capital, agrarian assets, and inputs, sizeable landholdings or possessing a sufficient scale of the production system.

PA technologies can also increase profitability and may even reduce the ecological footprints of farms, such as those driven by the leaching of phosphorus from dairy farms into streams and waterways. Farmers rely on recommendations from PA technologies such as drones and sensors to make insightful agronomic decisions on how much fertilizer to use/apply or which breed of seed to use rather than relying on their experiential knowledge of planting, sowing, harvesting, and fertilizer or herbicide application on the entire field, and dictation of nitrogen and phosphorus levels in soils (Boursianis et al. 2020; Klerkx et al. 2019). The widespread claim of economic and ecological benefits by agritech firms has generated significant investments from the state, public, and private sectors. For instance, the global precision agriculture market in 2019 generated revenue worth $9.56 billion (USDA 2019). The global agricultural robot market is expected to reach $11.58 billion by 2025 (The Aspen Institute 2019), a figure likely to rise as these technologies become more ubiquitous within production systems.

Recent social science research suggests that PA technologies promoted by agritech firms have the potential to reshape agrarian labor. However, a critical gap remains in our understanding of how this transformation will unfold, particularly from a theoretical perspective. Existing scholarship raises concerns about PA potentially disconnecting farmers from their land and traditional farming practices (Stock & Gardezi 2021; Gardezi and Stock 2021; Ogunyiola 2024). This disconnection could involve increased reliance on digital tools for farm management, distancing farmers from the physical aspects of their work (Rotz et al. 2019a; Tsouvalis et al. 2000). Furthermore, PA might lead to the encoding of farmers' knowledge within the technology itself, potentially transferring surplus value to agritech firms (Rotz et al. 2019a; Tsouvalis et al. 2000). While research has explored the social and economic implications of digital agriculture (Wolfert et al. 2017; Gardezi and Stock 2021; Ogunyiola and Gardezi 2022), there is a dearth of theoretically informed research on how PA might influence farmers' and farmworkers' production processes and how US agrarian labor might be transformed. This paper addresses this gap by providing a theoretically informed analysis of how PA might reshape US agrarian labor processes.

These issues raise concerns for the future of agrarian labor in the US and motivate this study to ask the following research questions: (1) *In what ways is PA dispossessing farmers of their autonomy and production processes?* (2) *How might PA reconfigure future agrarian labor in the US food system?* This study draws from the literature on agrarian Marxism, specifically the *agrarian question of labor* and *accumulation by dispossession*, to interrogate the profitable process through which farmers might be dispossessed of their autonomy and agrarian production systems and ways in which PA can transform future US agrarian labor, with prospects of benefiting high-skilled rather than low-skilled agrarian workers. The agrarian question of labor

offers a theoretical perspective to examine insights on agrarian transformation and politics associated with continuous innovation in the twenty-first century (Bernstein 2004; Levien et al. 2018). The remainder of this paper is presented as follows. The next section provides an overview of related literature on how PA is reconfiguring agrarian labor. The following subsection outlines the theoretical background of the agrarian question of labor and accumulation by dispossession. The methods section comes next, detailing the study site, data collection method, and the analytical approach for analyzing the focus group discussions (FGDs). The findings from the FGDs are presented in the next section. The findings presented are discussed, and the last session concludes the paper.

Literature review

This section documents how PA technologies are reconfiguring relations of agrarian production with implications for farm labor by critically appraising existing literature on the subject matter. We begin by presenting an overview of how PA is currently and likely to transform different strata of farm labor and marginalize certain labor groups. The second part discusses two theoretical perspectives: accumulation by dispossession and the agrarian question of labor. These perspectives are used to anchor research on precision agriculture and the future of farm labor through Marxist analytical traditions.

Reconfiguration of farm labor and marginalization of labor groups

Capital investments in food production systems primarily focus on technological innovations that require new skill sets, necessitating additional training of laborers for new tasks associated with the new suite of technologies (Acemoglu and Restrepo 2018). For instance, in the twentieth century, the mechanization of agriculture in America coincided with a substantial increase in employment in new agricultural industries and factory jobs, including farm equipment manufacturers (Acemoglu and Restrepo 2018). PA is transforming the technological apparatuses (hardware and software) used for farming through the integration of artificial intelligence and robotics, which are beginning to change how farming is conducted and the skills required for labor in agriculture (Ogunyiola and Gardezi 2022). Agritech firms promise that automation in agriculture enhances farm work, creating efficiency and productivity despite jettisoning unskilled and manual labor on farms. For instance, agricultural robots have already been developed to take over manual tasks, such as picking fruits and sorting them based on weight and nutritional value (Gardezi and Stock 2021).

PA might enhance labor-technology partnerships, where farmers are now meant to interpret yield maps produced by farm data collected by overhead and ground-based sensors and analyzed using physics-based models or machine learning algorithms. This means that agriculture will require workers with more advanced skills to work alongside agricultural robots and interpret complex maps developed through PA tools (Klerkx et al. 2019; Lowenberg-DeBoer et al. 2020), pushing unskilled laborers further into economic precarity. Although some scholars see PA as a solution for farm labor shortages caused by the limited and unpredictable supply of seasonal and migrant workers, as well as unfair labor practices (Auat Cheein and Carelli 2013; Christiaensen et al. 2020), the effects of automation and artificial intelligence are complex. While they may reduce the need for unskilled manual labor and support high agricultural productivity and profits for agritech firms and agricultural capitalists, they may not entirely eliminate these jobs but rather transform the agricultural workforce (Auat Cheein and Carelli 2013). This transformation will give rise to new roles and require existing skill sets to adapt to the changing demands of farm management practices, both on and off the farm (Ogunyiola and Gardezi 2022; Rotz et al. 2019b). This aligns with the notion that PA intensifies a long-standing trend of shifting farm expertise and decision-making away from traditional reliance on farmers' experience and intuition (Ayre et al. 2019; Eastwood et al. 2019). In recent years, farm advisors have become increasingly important, assisting farmers in interpreting data for strategic decision-making (Klerkx and Proctor 2013), and the development of PA technologies simply accelerates this trend. Nonetheless, there are concerns that PA, like past mechanization in agriculture, may benefit larger-scale operations with access to capital and potential economies of scale, potentially concentrating production in fewer hands (Wolf and Buttel 1996). In this sense, PA could be seen as promoting industrial agriculture models, perpetuating a trend where centralized agritech holds more influence over farmers (Krimskey and Wrubel 1996; Wolf and Buttel 1996).

PA also raises concerns about exacerbating existing racial and economic inequalities within the US agricultural system. While PA can increase productivity for higher-skilled workers (Bronson and Knezevic 2016a, b; Rotz et al. 2019a), it also displaces many low-skilled seasonal and migrant workers, who are often from minority racial and ethnic groups (Rotz et al. 2019b). Moreover, US agriculture has a long history of dependence on marginalized groups for low-skilled labor. If PA continues to displace these workers, it will disproportionately impact these marginalized groups. This concern is amplified by the long history

of racial discrimination in US agriculture, exemplified by chattel slavery and discriminatory lending practices by the USDA (e.g., the Pigford v. Glickman lawsuit of 1999 exposed bias against Black farmers seeking loans Cowan and Feder 2016). Limited access to capital due to such historical discrimination may further hinder Black farmers' ability to adopt PA technologies, potentially perpetuating these inequalities and class structures (Klerkx and Rose 2020; Sparrow and Howard 2020; Ogunyiola 2024).

Capital investments in innovating technological machinery that mediates the relations of food production have historically transformed and disrupted agrarian lives and livelihoods, (re)producing social inequalities and power asymmetries (McMichael 2009; Miles 2019). Likewise, PA technologies also reinforce the unequal mode of capitalist production and further marginalize specific labor groups (Klerkx and Rose 2020; Miles 2019; Nally 2016). As currently utilized, PA innovations may exacerbate existing power asymmetries between agritech and farmers, putting more power in the hands of a few agritech corporations or state actors (Fraser 2019; Rotz et al. 2019a). However, firms and farmers could responsibly innovate PA technologies, designing them to be sensitive and corrective of social inequalities, and wield them to support the growth of diverse communities of farmers and farmworkers while creating more jobs in this process (Ivus and Boland 2015). Yet the exigencies of capital accumulation within inequitable food production systems reinforce agritech's design and uneven deployment of PA. Agritech firms, through PA technologies, grab a large amount of farm data that is utilized to direct their innovations and investment opportunities, where the data is protected mainly by intellectual property rights that impede farmers' access and control (Fraser 2019; Rotz et al. 2019a; Stock and Gardezi 2021). The implications of PA regarding social inequalities remain gravely understudied, hence the impetus for this paper. Evaluating new strategies of agritech capital accumulation by dispossessing farmers, we situate this study within the context of accumulation by dispossession in the following subsection.

Theoretical perspective

Accumulation by dispossession

Marx theorized and described the evolution of capitalist social relations through *primitive accumulation*, which implies a series of events that contributed to producers' alienation from their means of production and subsistence; peasants become proletariats who have no choice but to sell their labor to the bourgeoisie. His classic analysis of primitive accumulation was grounded in the study of English enclosures where peasants were violently detached from their land and livelihoods (Levien 2011; Wood 2017). Marx contended that the process of dispossessing peasants from their land engendered the pre-conditions for capitalism. Dispossessed of land and without alternative livelihoods, peasants became a reserve army of labor whose surplus was needed for newly developed factories in the English cities. In this context, primitive accumulation emerged by separating producers from their means of production, which transformed farmers' livelihoods into capital and the workers into wage laborers (Marx 1987; Byres 2016). In this vein, capital is produced by detaching laborers from their property relations (Marx 1983). Therefore, the process of primitive accumulation transformed varying types of relations (social and property), which promoted capital accumulation and created new relationships between capital and labor. As it relates to food production systems, primitive accumulation refers to historically specific and contingent processes involving agrarian capitalists disrupting producers' social reproduction vis-à-vis the coerced reconfiguration of farm labor and the circulation of agricultural capital.

Harvey (2003) expanded upon Marx's concept of primitive accumulation, arguing that dispossession is a process that continues rather than simply a pre-condition for capitalism as theorized by Marx, which he termed *accumulation by dispossession*. Harvey (2003) suggests that current processes of dispossession emerge from the economic sphere, specifically finance and credit systems, evidenced in privatization, corporate consolidations, and other non-production/non-labor-oriented techniques exhibited by the capitalist. Harvey (2007) argues that accumulation by dispossession entails the act of taking away resources to concentrate wealth. This process involves various methods, including "commodification and privatization of land; the forceful expulsion of peasant populations; conversion of various forms of property rights to private; suppression of rights to the commons; commodification of labor power; suppression of alternative indigenous forms of production and consumption; colonial, neocolonial, and imperial processes of appropriation of assets (including natural resources); and in recent times, the additional techniques, such as the extraction of rents from patents and intellectual property rights" (Harvey 2007, p. 34–35). The capitalist's ceaseless pursuit of profit facilitates the capitalist class to reproduce itself and its dominance over the laboring class. Therefore, "accumulation cannot be detached from class struggle" (Harvey 1978, p. 116). Capital accumulation depends on reconfiguring labor strata to create a surplus during production. Capital accumulation is often done by increasing the number of labor hours for increased productivity, introducing machinery, as well as automating labor-intensive work processes (Harvey 1978). We situate our study on the idea of accumulation by

dispossession, given the genealogy of exploitation of marginal laborers arising from capital investments through corporate consolidation in food production systems. We assert the importance of using the accumulation by dispossession perspective in exploring the social ramifications of PA technologies to thoroughly understand existing and emerging ways in which PA might contribute to the dispossession of farmers and farmworkers. In discussing the implications of PA, we draw from Harvey's insights on rent and intellectual property rights (Harvey 2007). PA leads to the dispossession of farm information and intellectual property rights, significantly impacting labor. Next, we explore the introduction of PA through the lens of the agrarian question of labor in the next subsection.

The agrarian question of labor

The so-called *agrarian question* emerged from Marx and Engels' work on industrial capitalism. Marxist scholars such as Kautsky and Lenin, among others, began to apply Marx's labor theory of value in the industrial setting as a lens to understand the emergence of capitalism and the politics inherent in agrarian societies (Akram-Lodhi and Kay 2010a; Bernstein 2004, 2006; Levien et al. 2018). The concept of the agrarian question has acquired heterogeneous interpretations and applications over the past century, each revealing an essential aspect of contemporary Marxist discourse about the political economy of agrarian production (Byres 1995; Moyo et al. 2013). Kautsky expanded Marx's (1990 [1887]), Engels' (1950 [1894]), and Lenin's (1964 [1899]) agricultural transition perspectives to explore ways in which capital infiltrates agriculture and creates new forms of production (Kautsky 1988 [1899]. p 46), defining the agrarian question as "whether, and how, capital is seizing hold of agriculture, revolutionizing it, making old forms of production and property untenable and creating the necessity for new ones" (Kautsky 1988, p. 12). The agrarian question is built on the premise that the "penetration of peasant agriculture by capital is a decisive moment in the development of capitalism" (Levien et al. 2018, p. 860). Kautsky (1988, p. 297) asserts that "agricultural production has already been transformed into industrial production in many fields, and a large number of others can be expected to undergo this transformation in the immediate future. No field of agriculture is completely safe. Every advance in this direction must inevitably multiply the pressures of farmers, increase their dependence on industry, and undermine their security."

Following the original contribution from Marx, Engels, and Lenin, which is now referred to as the classical agrarian question (Bernstein 2004, 2006; Carlson 2018; Moyo et al. 2013), Byres (1995) framed the agrarian question as the problematics of politics (originating from Engels), production (from the studies of Kautsky and Lenin) and accumulation (from Marx and Preobrazhensky writings). Likewise, Bernstein's (2006) conception of the agrarian question focused on the economy (capital accumulation and production) and politics; capital provides a path for dispossessing peasants, all of which transform the agrarian mode of production and social interactions that agitate class tensions for peasants (Akram-Lodhi and Kay 2010a, b; Byres 1977; Levien et al. 2018). Bernstein (2006) affirms three interrelated aspects are visible from the classical agrarian question. First, how capitalism seizes the agrarian mode of production, creating a differentiation of agrarian classes. Second, how agriculture fosters industrialization, which emerges from the relations of production. Third, how capitalism creates political struggles for the agrarian classes (Levien et al. 2018). For instance, a key moment in the emergence of rural capitalism is connected to the appearance of rural wage labor and proletarianization as a consequence of the modalities by which agrarian capitalists dispossess peasantry from their landed property (Bernstein 2006).

While the agrarian question before neo-liberalization focused on land distribution problems, with neoliberal capitalism accelerating globalization, Bernstein (2004) argues that the critical component of the agrarian question concerns labor "now detached from that of capital, and which generates a new politics of struggles over land (and its distribution)." The central message of the *agrarian question of labor* explores the consequences of the infiltration of capitalist relations into the countryside, leading to the commodification of labor and accumulation based on increased productivity. Indeed, agrarian Marxism concerns itself with the question of "what are the political consequences of capital transition in the countryside" (Byres 1996, p.27). The emergence of PA, for instance, serves as an important avenue to explore how the changing political economy of agriculture and its implications of capitalist penetration into the countryside fosters capitalist development and undermines farmer livelihoods (Akram-Lodhi and Kay 2010a). The labor problem emerges from how the agrarian questions of capital transform agriculture through the expansion and intensification of capitalist farming relations, reconfiguring farming labor (Levien et al. 2018).

PA is transforming agricultural production relations, creating new ways of doing agriculture (Klerkx et al. 2019; Gardezi et al. 2022a; Ogunyiola and Gardezi 2022). The transformative agricultural production processes are an entry point to the classic agrarian question and the agrarian question of labor. The infiltration of PA requires that each case of dispossession be understood within the political, economic, and cultural context. Marx asserts that the process of dispossession plays out differently across geographies and social contexts (Marx 1978). In the US, dispossession

has historically been associated with the violent alienation of Native Americans from their land (Greer 2018; Murphy 2018). Alongside ongoing historical dispossession of land, recent social science research on precision agriculture and digital agriculture emphasizes new forms of dispossession in agriculture with the adoption of PA. Studies such as Fraser (2019) and Gardezi and Stock (2021) posit that farmers who interact with PA are likely to be dispossessed through displacement or data enclosures, knowledgeability, and autonomy, driven mainly by market domination to increase productivity and reduce production costs by exploiting agrarian labor.

The agrarian question of labor offers a theoretical lens to examine the contention between capitalist farming and the fragmented classes of labor (Bernstein 2006), consisting of landowners, agritech, farmers, and unskilled laborers such as hired, seasonal, migrant labor (Carolan 2020; Klerkx et al. 2019; Rotz et al. 2019b). Labor fragmentation occurs as traditional roles performed by farmers and wage laborers are taken over by automation. Some PA farmers now learn how to fly drones to know when to apply fertilizer to crops at specific locations, while hired, seasonal, and migrant workers are dispossessed of their manual farming skills (Ogunyiola 2024). The dynamics of innovation and accumulation are rescripting the demand for wage and unskilled labor. The changing nature of work further fragments the different groups of workers. The circulation of agrarian capital through PA technologies fragments labor classes "through insecure and oppressive and increasingly scarce wage employment in many places. Oppression and differentiation happen along the lines of gender, generation, caste, and ethnicity" (Bernstein 2006). Although we identify the intersectional dimension of oppression that might result from PA, we do not study this in detail, as the primary focus of this study is on how PA might transform agrarian labor. This study offers an essential step toward understanding the future of agrarian labor under capitalism. In particular, the agrarian question of labor allows us to interrogate how dispossessing forces and politics associated with capitalism influence the agrarian livelihood of farmers. In essence, understanding the forms through which PA dispossesses farmers and farm laborers.

Methods

To examine how PA dispossesses farmers of their autonomy, production processes, how farmers are responding to strategies of dispossession and the future implications for agrarian labor, this section discusses how primary data used in the study was collected, the process of developing a codebook, and the coding method used in analyzing data.

Study region

South Dakota and Vermont, states located in the US, were selected as study sites because they represent diverse characteristics of food production systems, such as differences in biophysical conditions, socioeconomic characteristics of farmers, different types of agriculture, sociopolitical and demographic characteristics, and varying types of technologies deployed. The diverse food production systems studied in each state were beneficial in exploring stakeholders' perceptions of the US food production system, where PA has the potential to restructure the lives and livelihood of farmers and farm workers and their engagement in agriculture as it relates to how PA is transforming labor dynamics, farming requirements on farmlands, and farmers' dispossession from their agrarian production process. Most farmers in South Dakota are large-scale growers of soybean, wheat, oats, sunflower, hay, and corn (USDA 2020a). PA decision support technologies such as sensors, drones, variable rate technologies, and yield monitors are now employed by many South Dakota farmers who engage in monocropping (Kolady et al. 2020). The farm ownership structure in South Dakota is essentially characterized by family and corporate farms. The average size of farms in South Dakota is approximately 1,459 acres (USDA 2020a). Vermont farmers operate small-scale farming systems, and some of these systems now utilize PA in dairy production, including automated milking technologies (Purdy 2016). In Vermont, most farms are owned by families who cultivate an average of 176 acres (USDA 2020b).

Participant recruitment

Food system actors were the target population for the study. Snowball sampling technique, through university experts (extension personnel) in South Dakota and Vermont who operate within the PA space and are knowledgeable about PA, was used to select participants who represent different actors in the PA space, which include (1) livestock, and dairy farmers, (2) technology developers, (3) state and county extension specialists and (4) non-governmental organizations (NGO). A purposeful sampling approach enabled us to effectively recruit participants who could provide us with rich and contextual information for answering questions pertaining to PA's social and ethical implications and how PA might have implications for farmers' autonomy and the future of agrarian labor in the US food systems (Patton 2002). The recruitment of participants was done through emails and a follow-up phone reminder. While 65 participants confirmed their attendance, a total of 52 people participated as research subjects.

To minimize tension and power dynamics between agri-tech and farmers (Bronson 2019; Rose et al. 2018; Tsouvalis et al. 2000) and to avoid excluding farmers' experiential knowledge from the dialogue and design of agricultural technologies (Ogunyiola et al. 2022), six different focus groups (four in South Dakota and two in Vermont) were conducted. These groups were categorized according to the participants in Table 1 and were intended to provide a forum for participants to freely discuss and describe any issues of dispossession associated with the adoption or use of PA by farmers. A total of six farmers were recruited, alongside 15 NGO personnel, 22 academia/extension professionals, and nine technology developers from South Dakota and Vermont. More than half of the participants in the NGO and academia/extension categories considered farming to be a secondary occupation. Therefore, the overall representation of farmers in the sample was much greater than six.

Data collection

To answer the questions this study explores, FGDs were used as a data collection strategy. FGDs were chosen because it has the potential to bring together different stakeholders who are relatively homogenous and who share similar characteristics on a particular social phenomenon of interest (Morgan and Krueger 1993; Kitzinger 1995). FGDs offer opportunities to gain multiple and shared or collective perspectives about the emergence and development of a social phenomenon, such as the emergence of PA and different stakeholder roles and experiences using PA within the food production system. Including different actors in the PA system is beneficial as it provides direct evidence of how the food system is changing due to PA. Through FGDs, participants openly share their perceptions about a social phenomenon, allowing researchers to gather rich data from a group that shares similar experiences rather than interviewing participants individually (Cyr 2019). FGDs provide an avenue for interaction among participants, stimulating discussion and exchange of ideas and providing insights that may not occur with a structured survey or even a guided interview with an individual participant (Morgan and Krueger 1993; Wilkinson 1998). Within the context of FGDs, participants might reflect and provide a more practical and empirical reflection of their past and current experiences rather than an individual interview, providing an avenue to understand the opinions and perceptions of participants that would be less accessible without group interaction (Greg et al. 2017; Krueger 1994; Wilkinson 1998; Hennink 2007). In this sense, stimulating participants through FGDs among US food system actors offered an avenue to articulate participants' perspectives and experiences vis-à-vis the development or adoption of PA technologies. Recent studies, such as Brown et al. (2023); Ogunyiola and Gardezi (2022); Rotz et al. (2019b), have utilized FGDs with different actors and stakeholders who engage with PA in the agricultural system.

Data was collected from six FGDs that emerged from workshops held in South Dakota (4 FGDs) and Vermont (2 FGDs) between October and December 2019, with each FGD including similar types of food system actors. FGDs were administered during workshops in both regions. We encouraged participants to discuss their perceptions of the main topics on which the study is situated. The overall focus of the FGDs was predicated on highlighting opportunities and risks PA technologies produce in both regions. A sample of FGD questions discussed during the workshop by participants are: *How do you think automation will change farming? How might precision agriculture enable the automation of work? Will precision agriculture increase or decrease the overall labor requirement?* In both South Dakota and Vermont, the duration of FGDs was between 90 and 120 min. The confidentiality of participants was protected by using pseudonyms that removed any identifiers. Video and audio recordings were used to document the entire FGD sessions.

Table 1 FGD participants by categorization

Participants	South Dakota	Vermont	All participants
Farmers	4	2	6
NGO/Government regulators	10	5	15
Academia/Extension	14	8	22
Technology developers	6	3	9
Total	34	18	52

Analytical approach

We used an interpretive qualitative approach to analyze FGD transcripts from workshops held in South Dakota and Vermont (Ogunyiola and Gardezi 2022; Ogunyiola et al. 2022; Yanow 2000). This approach allowed themes to emerge from the theoretical frameworks (accumulation by dispossession, the agrarian question of labor, and agrarian Marxist literature) guiding our study. Using both inductive and deductive coding, we identified meaningful pieces and themes in the transcripts (Braun and Clarke 2006, 2020). We generated a codebook using a procedure outlined by MacQueen et al. (1998). The codebook contains codes, their definitions, and the criteria for including them in the analysis (see Table 3 in the Appendix). We used NVivo QSR 12 software to code and manage the data. Coding was conducted in four steps: (1) transcribing six audio recordings and replacing participant names with pseudonyms; (2) systematically coding the transcripts; (3) identifying emerging codes; and (4) grouping and developing themes. Some of the codes that emerged from the FGDs were labor, change in skills, training, labor shortage, data rights, and privacy. These codes were then

categorized into themes, such as capital accumulation and dispossession of farmer autonomy, future labor dynamics, and skills and workforce development. In the next section, we detail emerging themes from the FGDs on how PA is influencing farmers' autonomy and the future agrarian labor in the US food system. In the discussion, we draw upon the theoretical perspectives engaged in this study to illustrate the broader implications of our research findings.

Limitation

While the FGDs drew from different stakeholders who interact with PA in the agricultural production system, the study is limited by a lack of data from farmworkers and migrant workers, who constitute key actors in the US food production system. Farmworkers and migrant workers are crucial to the US food system, and their perspective on how PA affects them would have been valuable. However, we were unable to gain access to these individuals. The lack of representation of farmworkers and migrant workers in the FGDs limits the generalizability of the study findings, as their perspectives may differ from those of the other participants in the study. Farmworkers and migrant workers may have unique insights into the social and ethical implications of PA due to their experiences working in the US food system. Despite this limitation, other actors (farmers, extension personnel, agritech, etc.) in the agricultural production system can offer insight into the changes experienced by farmworkers and migrant workers. In light of this limitation, this study provides valuable insights into the perspectives of how PA dispossesses farmers of their autonomy, production processes, how farmers are responding to the strategies of dispossession, and the future implications of agrarian labor. By incorporating the study's findings, PA can be developed and implemented in a manner that is socially responsible and equitable for stakeholders.

Results

This section describes emerging themes discussed in the FGD transcripts by participants to answer the following research questions: (1) *In what ways is PA dispossessing farmers of their autonomy and production processes?* (2) *How might PA reconfigure future agrarian labor in the US food system?* Using the qualitative interpretive analysis described above, we identified three distinct themes that emerged from our FGDs: (1) Regimes of dispossession and capital accumulation through PA, (2) Future labor dynamics, and (3) Skills and workforce development.

Regimes of dispossession and capital accumulation through PA

Technology developers from South Dakota and Vermont envisioned precision agriculture (PA) as a technological solution to improve social, environmental, and farm productivity outcomes. They believe PA can address existing challenges in agriculture. Other FGD participants also acknowledged the potential benefits of PA, recognizing its ability to enhance farm efficiency and productivity, reduce pressure on natural resources, and ultimately boost farmers' income. For example, a technology developer from South Dakota described PA as "using technologies for better production in agriculture."

Despite the narrative promoted by technology developers highlighting PA's environmental and productivity benefits, other FGD participants presented a contrasting view. They emphasized that PA disrupts the entire food production system—socially, economically, environmentally, and technologically—affecting various stakeholders in agriculture. Concerns were raised about how PA is currently designed and implemented by agritech—as farmers in South Dakota and Vermont adopt and engage with these technologies—resembles previous technological innovations in agriculture, such as genetically modified crops, which have ostensibly revolutionized agriculture.

Farmers from South Dakota and Vermont shared their experiences with adopting PA technologies, suggesting that PA might simply be another step towards further automation of agricultural production processes. Automating agricultural processes could lead to fewer manual laborers and increased reliance on machinery. An extension personnel from Vermont echoed this sentiment: "We have had a ton of automation already, just like a continuation of the trend we have already seen with regard to fewer manual laborers, more machinery."

Indeed, the adoption of PA technologies is accelerating the automation of farming processes in South Dakota and Vermont. PA technologies such as drones (Fig. 1), big data, machine learning algorithms, and variable rate application technologies (Fig. 2) are replacing traditional farming practices (e.g., scouting, planting, fertilizer application), which is having a mixed impact on the expertise of the farmer. FGD participants, particularly farmers, assert that the continuous automation of the food-production system eliminates the 'drudgery work' of agricultural production. It reorganizes farmers' work-life balance. According to one farmer in South Dakota, automation is reorganizing "farmers' work-life balance," thereby making it easier to have more productive work time. Another farmer from Vermont states that PA "changes the quality of life by freeing up time for personal pursuits. Because it does those things you just

Fig. 1 Drone operated on a farm in South Dakota to collect field information (courtesy: Deepak Joshi)

mentioned [new dairy farming methods lead to bigger gains in milk production as a result of better nutrient management], it changes the quality of life. People can actually live on the farm in a way that they haven't lived on the farm before." Similarly, a farmer from Vermont emphasizes the time saved through dragline manure application: "Another thing that I see really helpful with precision agriculture is just the opening of time for the family farms. Moving to precision agriculture, you can use draglines instead of hauling manure around because manure management is such a big issue in the Vermont context of agriculture. Moreover, if we can dragline, I can put 2000 gallons a minute into my fields under the ground, reduce phosphorus runoff, and increase my ammonia uptake. Rather than shipping seven thousand-gallon trucks, I can empty a pit in a day rather than a week. This gives the farmers a lot more time." This perspective on PA suggests a potential increase in control and autonomy of their time for some farmers while acknowledging potential negative consequences for farmworkers.

While farmers in South Dakota and Vermont acknowledge the potential for PA to positively impact work-life balance and autonomy over time invested in farming activities, FGD participants worry about PA's ability to dispossess farmers of control and autonomy over their production process. A farmer from South Dakota expressed this concern, stating, "One of my concerns about big data [PA] is that we have seen more corporate-level decision-making, especially in the livestock and crop industry. I have heard throughout my farming career and prior to my farming career about how real crop agriculture, a lot of the agriculture is going to go. It's one of the challenges that the more information they [agritech] have, I am going to be somebody out there just doing the job for another company and won't have any decision." Farmers worry that big data could lead to more corporate control over farm decisions, with farmers becoming mere managers following instructions set by large companies. As PA intensifies, farmers may rely on data-driven directives rather than their own experience and knowledge, potentially losing the autonomy and decision-making power that are hallmarks of traditional farming. Therefore, efficiency gains notwithstanding, the reorganizing of farming through the adoption of PA has facilitated capital accumulation by agritech and several forms of dispossession, mainly farmer autonomy and control of the production process.

Data dispossession and digital lock-in

Farmers in South Dakota and Vermont are unevenly adopting PA. Yet, these technologies are related to components of the well-known 'ever-growing' industrialization of agricultural production systems that erode farmers' autonomy and control over production systems. With the adoption of PA, farmers' autonomy and control of production processes might be eroded, and farmers become collectors of farm data and information. As one industry expert from Vermont

Fig. 2 Monitor showing control of other precision technologies and variable rate application. (Source: John Deere https://precisionagricultu.re/john-deere-and-the-birth-of-modern-precision-agriculture/)

asserts: "We are right in the middle of precision agriculture; we are harvesting just an enormous amount of data every day on every milking [process of milking dairy cows]." Agritech firms have built an algorithmic ecosystem of data collection, a novel accumulation strategy that (re)produces asymmetric power relationships between farmers vis-à-vis data ownership and transparency, undermining farmers' autonomy and control of production processes.

Data dispossession is sustained through contracts and end-user agreements designed by agritech that farmers must sign to utilize certain PA technologies. For instance, to use recommendations that can potentially increase crop yields, farmers sign contracts with companies (e.g., Climate Corporation) and their products (i.e., FieldView) to receive specific recommendations that promise to increase crop productivity. When farmers give up their rights in exchange for the perceived benefits of PA, they lose ownership and access to their farm data. Farmers are unable to determine how agritech firms will use their farm data in cases where consent is required.

In addition to concerns raised by FGD participants about data ownership, farmers feel as if they are losing their autonomy over PA equipment they purchase as agritech restricts farmers' rights to repair their PA-integrated farm machinery, yet another modality of dispossession. Regarding this issue, industry experts justify creating these exclusions in the design of new technology, as identified by a technology developer in Vermont: "Our model is similar to other large agricultural equipment developers that you have to be a certified qualified 'tech' to work on a robot, you cannot just, somethings you can touch but, in most cases, it requires, [a certified technician] to work on it. So, I mean, we kind of have the same concept with John Deere regarding accessibility to the equipment and a lot of that goes back to safety and proprietary, you know, investment, things that we've done that are secure." Even when these farmers have the technical 'know-how' to fix the PA tools they operate, agritech contracts and end-user agreements prohibit farmers from modifying or repairing any part of their machinery. Contractual obligations make it harder for farmers to access data, reducing their agricultural production autonomy as they adopt these technologies. But then there's not only the issue of repairing equipment. A farmer in South Dakota stated: "Maintaining the hardware isn't bad; it's all the subscriptions I got to pay every year to keep it running. The software is more expensive in the long run than the hardware, and they know that. I mean, Deere knows that Climate knows that, Trimble knows that."

Although agritech firms access large amounts of farmer and farm data to improve productivity and efficiency on and off the farm, this practice creates a pathway to observe and predict farmers' behavior. FGD participants believe farmers are dispossessed of their autonomy and production process through agritech's data grab. Although farmers already buy seeds and other recommendations from agritech because of other previous agricultural technologies, PA is facilitating a rapid extraction of farm data that allows agritech to 'add value' to the aggregated data, which is used in making recommendations on the kind of technology and agricultural inputs (e.g., chemicals, seeds) that farmers need to buy. Farmers who subscribe to and adopt PA technologies may face a potential digital lock-in, which confines them to a specific agritech ecosystem. This digital lock-in occurs because the data that farmers generate through PA technologies are exclusively evaluated by the particular agritech firm, and the recommendations they receive are limited to the products and services provided within the same agritech ecosystem. Consequently, farmers may have limited options and choices available to them since they are constrained to the recommendations generated solely by that agritech ecosystem. Agritech's dispossession of farmers' autonomy through exclusive data access and digital lock-in functions as a novel accumulation strategy that farmers believe constrains their ability to make insightful farming decisions outside of the agritech ecosystem that they are subscribed to. One academic from Vermont, who also farms, argues: "I see the robot system already having that database of seed or the hundred different varieties or whatever you select to choose from. When you hit 'go,' it says: Where am I going? You tell it, and it looks up whatever data—historical yield data or whatever you put in for input—and says: I would recommend this and this seed. And you pick which one." Farmers' reliance on algorithmically derived recommendations from agritech constrains their decision options, which legitimizes industrial agriculture models of accumulation. This contributes to the already existing trend of technological innovations that reduce farmers' autonomy and make them question their identities as producers.

Dispossession of farmer identity

The identity of farmers is being (re)negotiated through the emergence of PA technologies. Farmers are increasingly being perceived and perceiving themselves as 'data gatherers.' As one extension expert from Vermont says, "The best farmers are observational data collectors, every single minute of every single day. They may not perceive themselves as data scientists, but information collectors." Farmers' active efforts in collecting farm data through PA create a significant shift in roles performed by farmers and nontraditional actors within the agricultural production system, changing what it means to be a farmer. Farmers are abstracted from their traditional cultivation roles because of data generated through PA sensors, drones, and decision support systems.

For instance, a farmer in South Dakota contends that PA technologies have the "ability to process data so much more quickly than we can as humans—and lots of data—and to be able to make a decision and change on that." The reliance on these technologies is changing the roles of farmers and agronomists and how extension personnel offer agronomic advice to farmers. These changes in roles are consistent with capitalist transformations of agriculture through the influx of capital and the intensification of machinery that transforms labor relationships between agritech, farmers, and farm workers. These changing roles can compromise farmers' autonomy, thrusting them into an uncertain future whereby agritech fundamentally reconfigures the strata of agrarian labor. We summarized insights from FGDs about the implication of PA as a strategy for capital accumulation and dispossession of farmers' autonomy and control of the production process in Table 2.

Dispossession of farmers' experiential knowledge

Farmers choose to use PA because it is superior, more accurate, and trustworthy, even if it doesn't work perfectly every time. A South Dakota farmer highlighted: "You could make an argument that you can be like, my yield map isn't right, my soil sample was not taken correctly, my remote sensing all has to be true. Like, there's a reason they lack confidence, but at the same time, all those are valuable if they're done correctly." Farm information can be collected by sensors that are attached to farm equipment, such as tractors. Analyzing these large farm datasets is a complex task that requires advanced computational skills, especially for farmers and farm workers who do not possess these skills. An academic from Vermont pointed out that this new knowledge was both advanced and challenging for farmers to access: "As that new information comes their way, how do you make sense of that? The concern I have is the data become so sophisticated and encrypted and inaccessible that even if they gave it to the farmer, he or she wouldn't know what to do with it or how to use it." Farmers may not know how to utilize the data collected by agritech through their farm equipment, calling into question the value of farmers' experiential knowledge in light of new knowledgeability formed through PA.

A non-governmental representative from South Dakota discussed how automation in agriculture impacts farmers' knowledge: "I would hope that automation makes us more efficient with our natural resources so that we never get the gully in our fields, right, so that we figure out how to manage our fields and keep it healthy, and preserve our carbon and things like that. But I am concerned where a human doesn't unlearn something once they've learned it, so the technology could just run wild." This sentiment recognizes some uncertainty surrounding the use of automation in natural resource management. Although it is acknowledged that automation can lead to increased efficiency in resource utilization, potentially preventing environmental damage and promoting sustainability, there are concerns about human overdependence on automation. This overdependence can lead to a decline in essential skills necessary for effective resource management. Additionally, a lack of human oversight could allow the technology to operate unchecked, potentially causing unforeseen problems that humans would not be equipped to address due to a loss of relevant knowledge.

PA can lead to farmers losing their autonomy and knowledgeability. This is because farmers are becoming disconnected from their traditional farming practices. An academic from Vermont raised doubts about the purpose of automation in agriculture: "What are we replacing in terms of actual connection? Hands in the dirt versus just being dashboard where you're clicking buttons and stuff is happening out there." Another extension personnel in South Dakota stated that a farmer's experiential knowledge is crucial to enhance productivity: "And I think the autonomous farming will further lead to a degradation of our natural resources. I think that the human factor has to be there making those decisions on how we're going to do this, and just pushing buttons and letting drones go will lead to further degradation of our natural resources. And it's a relationship to owning a physical asset, the earth, and realizing what that natural system is providing in that process; whereas, when we go autonomously, we're starting to ignore that, and it's

Table 2 An overview of insights from FGDs on PA as a strategy for capital accumulation, dispossession of farmers' autonomy, and agrarian labor in the US food system

Regimes of dispossession and capital accumulation through PA	Agrarian labor dynamics
• Farmers lose ownership and access to data protected by end-user agreements or legal contracts • Manipulation of farm data • Extraction of valuable farm information • Farmers over-reliance on algorithm recommendations • Farmers become data gatherers • Farmers lose the right to repair their PA-integrated machinery • Substitution of farmers' experiential knowledge with PA	• Enhance efficiency and productivity • Reduce the amount of work on the farm • Address agrarian labor supply shortages • Displacement or replacement of manual laborers • Farmers become managers of a network of technology • (Re)producing inequalities among farmers and farmworkers.

the black box that makes the decision on what we're going to do."

Land dispossession

PA has the ability to transform the way farmers use their land, which justifies the continuing consolidation and homogenization of farmlands into the hands of a few large corporations. FGD participants agreed that the food production system is becoming more consolidated and homogenized due to the emergence and adoption of PA through agritech's grabbing of farm and farmer data. This perspective is held by one extension personnel from Vermont who described PA as a technology designed for larger-scale farmers who are engaged in growing monoculture crops such as corn and soybean: "I think one of the really big questions that come up in my mind is *what are these tools being developed in order to optimize?* Most of the technological progress that we've seen in agriculture over the last century has been optimizing monoculture, optimizing commodity production, optimizing larger farms." The mechanism of consolidation and homogenization of food production systems is further supported by a technology developer in Vermont: "In the industry, we're seeing, sort of, call it 'consolidation,' or monoculture emerging in the technologies as well. So, you know, row crops are the first target for precision ag because you have a ton of land you can manage all with the same method, all have the same big data set, to learn about it. And the small producers or the diverse producers are left out because it's not an attractive economic target. But it also reduces the resiliency to have people like John Deere, Monsanto, or Syngenta, you know, playing such a large role in controlling so much production." An extension agent from Vermont echoed these concerns of corporate consolidation: "All of a sudden, all the best land gets concentrated in very few hands because they know the information of every sinkhole, they know every highly nutritious soil type." Therefore, PA supports specific modes of farming and farmers that allow for and support capital intensification.

Future agrarian labor dynamics

Agritech firms' data grab not only dispossess farmers of their farm data but also contributes to the reconfiguration of farm labor. Our results show that FGD participants in South Dakota and Vermont agreed that PA technologies are contributing to the changing future of agrarian labor just like previous innovations such as tractors and other mechanized farm equipment have revolutionized agrarian labor. FGD participants envisioned the adoption and application of PA as an augmentation strategy capable of assisting farmers and farm workers in improving their farm tasks. FGD participants also expressed concern that PA might displace or replace some farm workers. Agritech envisions the future of labor as enhancing efficiency and productivity, where these technologies are beneficial insofar as they can reduce the amount of work on farms and address the labor supply constraints of rural agriculture. As such, PA is defined by a technology developer in South Dakota as "supporting management decisions for improved resource use efficiency." However, agritech's access to and control over data collected from production systems positions these firms as a formidable force in the political economy of agriculture. The idea of agritech being a formable force is echoed by a farmer in South Dakota as to how agritech firms are creating new opportunities in the agricultural sector: "They [agritech] are collecting yield data, lots of weather data, soil conditions data. The challenge is making that all work together. We need someone to analyze, someone in the middle that can actually move that through." This suggests that there will be a demand for specialists such as data scientists, agricultural engineers, and precision agricultural consultants to make the enormous amount of data collected useful for farmers.

Some FGD participants imagine that farmers' roles will change, but they will remain critical for ground-truthing or verifying the recommendations produced by PA technologies. An extension personnel from South Dakota noted: "I feel like the farmers' knowledge of the field and the history of it is really important because they can pick out zones and areas of the field they know aren't producing well. That way, we can make recommendations made by artificial intelligence that are more suitable for farmers' fields." Other participants envision farmers managing networks of PA technologies that will be instrumental to agricultural efficiency and productivity. One farmer from South Dakota expressed: "I envision managing a fleet of robots or something along that line, where maybe I'm the tender truck driver that's moving them from field to field and managing ground truth and doing that sort of thing." Indeed, PA casts farmers as office managers of technologies, transforming agrarian production processes into collecting large amounts of data from crop production and land rather than the previously held roles of cultivators.

Participants observed that farming operations would be transformed from physically scouting their farms for pests "by-the-foot approach" or applying fertilizer to using mental calculations in the office. Although farmers have historically managed their farmland by determining the right amount of fertilizer, for instance, this is following the trend with new innovation in agriculture, as one extension personnel from South Dakota believes that: "There is a shift happening, and farming is becoming more mental [sitting in the office and processing information] rather than physical [going to the field to attend to crops]. I mean, there's a lot

of mental stress. I feel like all my husband [who manages our farm] does is constantly run calculations in his head. So yeah, I think there's a perception from the public that some of us are becoming lazy just because we depend on technology, but farming is becoming more mental than physical labor." Although PA allows farmers to be off their farms more than ever before, the techno-optimist dilemma PA presents further abstracts low-skilled farm labor and shifts the labor required to high-skilled to conduct daily framing operations from simply scouting the field to reading farming recommendations from PA technologies and farmers working from their remote offices.

Some participants did not imagine farmers to be as crucial in the near future as they are today. A technology developer envisioned a future where farms would be without farmers: Our [firm's] concept is complete autonomy. Maybe it's called level five autonomy. It's the idea that humans do not need to physically sit in the machine. Today, when we farm, farmers are pushing hard in the middle of the night trying to get harvest done, and they get tired. But the [autonomous] machines will not get tired."

Many FGD participants expressed concerns about who will get displaced or replaced by PA. An NGO worker in South Dakota explained: "I want to comment on this idea that the advancement of technology in agriculture will promote workers and create opportunities for small farms. History tells us that doesn't happen. Small rural towns had all died in the previous technological transformation, and what killed it was not the tractor, but that because of the tractor, you consolidated into larger farms that needed less labor. So, you want to be very careful when managing the transition to PA that you're not compounding that issue. Rather than more jobs, you're very likely looking at fewer jobs." Indeed, the transition to prepare the agricultural workforce from an analog to a digital setting requires the fundamental rewiring of the labor force and examining this transition under the broader political economy of agriculture.

Agritech's innovations are threatening the expertise of manual laborers. The emergence of PA will force precariously employed and marginalized farm laborers to be displaced or replaced. FGD participants in South Dakota and Vermont substantiate the perspective that manual workers are likely to be displaced or replaced due to the infiltration of PA in agricultural production systems. The Vermont dairy industry, which relies heavily on undocumented migrant workers, is at risk of displacing or replacing farm workers through increasing automation of milking systems. One dairy farmer in Vermont asserts that "we have so much manual labor coming from immigrant communities [who work on the farms]." However, this large amount of manual labor from migrant workers is replaced or displaced, reducing the need for migrant workers on the farms. Another dairy farmer from Vermont supports this perspective, suggesting that the infiltration of PA in dairy farms is a continuation of the trend that abstracts farmers of their production process because of machines which "in many cases, is displacing 50% of labor on the farm." Indeed, adopting PA is transforming the manual labor required on the farm, although PA technologies can alleviate shortages of the agrarian labor force in Vermont. Farmers in South Dakota, primarily those who grow corn and soybeans, are experiencing a similar fate, where machines create an opportunity for the continuous displacement and replacement of manual labor. A farmer from South Dakota, drawing from a historical event in the manufacturing sector, envisions that the labor force in agriculture will be "replaced if the only thing you're doing is turning around at the ends and doing a little more monitoring. And you look at history, and you look at manufacturing, and those jobs that are consistent and repetitive are the ones that technology has replaced."

Ostensibly innovations of agriculture, PA technologies are accumulation strategies that transform agrarian lives and livelihoods, having the effect of (re)producing inequalities in the production system that disproportionately affect lower-skilled workers. One industry expert in Vermont supported this finding: "If production is part of labor and capital, you increase the capital part and reduce the labor part. So, you created inequality." Although increasing capital and machinery can increase efficiency, on the one hand, it can replace the amount of lower-skilled labor required on the farm, which eventually fosters the capitalist nature of agriculture. This process is evident in Vermont, as described by one extension personnel from Vermont: "When I look at a farm system, particularly in Vermont, I love when a farmer shows up with his robots. Because it does those things you just mentioned, it changes the quality of life. People can live on the farm in a way that they have not lived before. But it displaces, if you want to take it to an extreme, if it displaces a migrant crew that is shipping their income back to Mexico, you know, we can't be devoid of that. If we expect that, we will have a lot of new technology on the farm." Migrant and low-skilled workers are losing their livelihoods with the development of PA technologies that replace their manual labor. Techno-optimistic imaginaries of PA-mediated production systems enable agritech and agrarian capitalists to transform the relations of production in ways that render precarious farm laborers as surplus with reduced employment opportunities. Farm owners and operators that utilize PA technologies increasingly become data harvesters, where new practices reduce the labor demands required for agricultural production on the field.

FGD participants highlighted consolidation trends in the food production system, where farms are becoming larger and more industrialized. These larger farms are more

likely to adopt and benefit from PA technologies. However, the adoption of PA could further accelerate consolidation, potentially leading to a decline in the number of farmers and farm workers. One academic from Vermont opined that "so like it used to be everybody sort of had their family farms, and then it's like fewer and fewer people, you know, fewer and fewer farmers on a much bigger farm need access to workers, and then now those workers may be getting sort of displaced." Agritech restructures production relations by developing more machinery capable of automating the work process. With the consolidation of the food system through the digitalization of farms, FGD participants suggested that PA technologies will create a concentration of profit in the hands of a few stakeholders who will control and own farmland, where market concentration will become accessible for agritech and few farmers who can transition to PA. A farmer in Vermont asserts: "Different types of technology continue to push market concentration to land, land ownership, and the concentration of profit into fewer and fewer [hands]. So, I think there's a displacement and just such an interplay between the two. And I don't think it's just one displacing the other, and I think they can actually move in the same direction." Future agrarian labor will be driven by agritech, a few farmers, and laborers who can upgrade their skills to transition to PA to remain relevant to control land and market for agricultural commodities.

Skills and workforce development

The emergence of technology in society is inseparably entangled with politics; their design is not value-free; hence, they are not intrinsically good, bad, or neutral. Agritech's data collection practices have a significant impact on the way agricultural labor is structured. Farmers and farm workers must acquire new skills to remain relevant in the food production system, as PA challenges their current skills. Some FGD participants believe PA technologies affect various food system actors' competencies and experiential knowledge. PA technologies necessitate collecting, curating, and analyzing large data sets. Most farmers in South Dakota or Vermont do not possess the capacity to store or analyze large datasets. A non-governmental worker from South Dakota shared her thoughts on her interactions with farmers: 'A lot of times they lay out a bunch of memory cards [with large data sets stored in them] in front of you – "well, here it is" – they haven't done anything with it.' The process required to move from data to information and knowledge changes the requirements for skills in agriculture. One farmer from South Dakota admitted that they would need "one or two people on the operation to be really good at math and computers. Indeed, PA is redefining farmers' roles and the skills needed to succeed under PA, leading to farmers becoming 'digital laborers.'

Some FGD participants presented ideas that could aid in developing skills and a workforce for future agrarian labor. One was to prepare farm advisors for a new kind of role, which involved the interpretation of recommendations generated from PA technologies rather than relying on their own intuition or knowledge. An extension personnel from South Dakota claims that "there is still going to be a need for people that can explain the why [results of the model] to a grower who is looking to implement a practice… More recently, my job has been to open the 'black box' and explain to the farmer what is inside it. Therefore, it is still important to have those boots on the ground." Another farmer from South Dakota expressed that not only farmers will have to upskill but also those who will be assisting farmers with their decision-making, "the troubleshooting and the technical aspect of being able to keep some of these things [PA technologies] running and working correctly."

The ongoing reconfiguration of agrarian labor due to PA has necessitated some farmers and other actors in the food production system to gain new skills similar to those required by previous agricultural innovations. Farmers and agronomists increasingly rely on drones and ground-based sensors attached to farm equipment to gather significant agricultural data. For example, soil fertility recommendations use PA technologies, which are replacing workers on farms in South Dakota, and automated milking systems in Vermont, which replace milking crew workers. One extension personnel from South Dakota asserts that PA technology allows farmers to remotely monitor plant health and prescribe treatment where and when necessary: "Now I can tell the plant's health without physically scouting them. A few farmers have successfully utilized yield maps or disease maps to plan and make necessary improvements in agronomic decision-making, including applying nutrients to farm fields. With the power of GPS technology and information produced by databased PA models, farmers can precisely identify locations and then apply site-specific agronomic decisions rather than only relying on intuition and labor-intensive data collection procedures (e.g., physically scouting land for pests and diseases). Although PA might reduce the amount of time farmers and farmworkers spend on their fields, it is abstracting farmers from their production process.

With end-user agreements protected by intellectual property rights, agritech ensures that agrarian production selects specific skills, reconfigures identities, and rewires the knowledgeability of the farmers. Although farmers are contractually prohibited from fixing the PA technologies, PA requires farmers to learn more technically advanced skill sets, such as flying drones, that are now required to manage

their farms. The time and effort required to acquire new technical skills for PA technologies and manage complex AI-powered machines may overshadow the value of traditional manual tasks and the experience-based knowledge of farmers.

In essence, PA alters the current and future social identities of farmers. The social identities created under the emergence of PA are substituting the traditional identities that farmers possess. For instance, a technology developer from Vermont explained how previous agricultural technologies historically influenced the skills and identities of farmers: "Before tractors existed, farmers were not mechanics, right? But we need to recognize that where the most inertia comes in is a cultural, identity, and emotional issue in terms of switching jobs and acquiring new skills. You know, a certain cachet and identity of being a farmer exists." Agritech's reconfiguration of farm labor by dispossessing farmers' autonomy and control over the production system through PA technologies ultimately threatens the social identities of farmers as they are pressured to acquire new skills to remain productively employed in farming and frantically strive for key performance indicators of efficiency and productivity. In the next section, we discuss the implications of our findings.

Discussion

PA technological interventions in the production systems of South Dakota and Vermont are leading to a consolidation of power for agritech and the further stratification of the agrarian labor class. Agritech firms design PA for large holding and monoculture agriculture systems, and the majority of smallholding and marginalized farmers are excluded. Similarly, legal contracts and licensing agreements backed by intellectual property rights prohibit farmers from owning their farm data and 'tinkering' with their farming equipment. Agritech firms' accumulation of capital is predicated on alienating farmers from their means of production, dispossessing farmers from their data, and farmers' control and autonomy within their production system, thereby capturing labor, land, and data about farmers' production processes in Vermont and South Dakota (Li 2011).

Large-scale land acquisitions or consolidations displace local populations, often leaving them with limited job opportunities. Corporations benefit by acquiring cheap land and labor, effectively disempowering local communities. This process captures labor through low wages and minimal job creation to maximize profit (Li 2011). Emerging technologies exacerbate this exploitation, where advances in PA technologies are fueling the financialization of farmland, previously hindered by complex ownership structures (Duncan et al. 2022). The ongoing automation in agriculture transforms farmlands into financial assets, attracting agritech firms that benefit from increased agricultural output and land value. This integration into a global market potentially leads to concentrated land ownership and threatens farmers' autonomy as financial actors and agritech firms gain more influence over land use decisions. Additionally, farm data collected through PA technologies further contributes to this financialization, potentially resulting in farmers losing ownership of their land (Duncan et al. 2022).

Drawing insights from the theoretical perspectives of accumulation by dispossession and the agrarian question of labor, our findings have several implications. First, our results show that PA introduces new perils to farmers' autonomy and control over production processes. Despite agritech's discursively articulated solution to productivity gaps, resource depletion, and ecological degradation, agricultural production system stakeholders must consider the social implications of adopting PA. However, such techno-optimistic discourses about PA's potential to circumvent famines in a climate-ravaged future entice farmers to adopt PA, irrespective of whether the social implications of these technologies are well understood (van der Burg et al. 2019; Ogunyiola and Gardezi 2022; Gardezi et al. 2022a). FGD participants are concerned about the potential to deliver efficiency and productivity in light of regimes of dispossession of their production process. Dispossession in the food production system has historically occurred due to the state unlocking the value of land for capital accumulation by the private sector (Li 2014; Levien et al. 2018). Land, as of today, is not as easily alienated as in the era of indigenous genocide. The digital representation of land and food production systems manifests agritech's control over big data. The strategic absence of legislation and regulation on PA technologies in the US enables agritech to gather data about landed production systems (Stock & Gardezi 2021; Sippel 2023; Duncan et al. 2022). Through the framework of accumulation by dispossession, agritech firms are enrolling farmers to adopt PA. Extensive data collection by agritech firms focuses on farm activities like yield prediction, field scouting, and planting or seeding. Data from these farming activities becomes a source for the digital extraction of farmer knowledge and numerous farm management practices, which are then coded and stored for potential future automation of farm labor, potentially dispossessing farmers' livelihoods (Gardezi and Stock 2021).

Undoubtedly, as farmers and farm workers are separated from their means of production, their livelihoods are transformed into capital-driven enterprises (Byres 2016; Harvey 1978; Marx 1987). Agritech's capital accumulation through PA largely depends on reconfiguring the labor strata to create a surplus during the

production process by introducing machinery and automating labor-intensive work processes (Harvey 1978; Bernstein 2006). The current ecosystem design of PA represents a current modality of dispossession through farmers giving up their farm data to agritech who are not explicit with farmers on how their data will be used. Results from our FGDs further reveal that the lack of transparency offers immense opportunities for agritech through transforming farm data, directing farmers to purchase certain forms of inputs, and creating recommendations that farmers require to improve production and efficiency (Barrett and Rose 2022; Schillings et al. 2021; Ogunyiola and Gardezi 2022). Farmers lose their ownership, access, and control over data and their decision-making ability due to a lack of transparency. The lack of transparency erodes farmers' autonomy, undermining sustainable farming as agritech firms have more advantage over data collected by farmers. Information asymmetries could potentially impact how power is distributed and reduce farmers' autonomy in the food production system (Coble et al. 2018; Carbonell 2016; Fraser 2019, 2020; Posadas et al. 2023; Wolfert et al. 2017). Therefore, the infiltration of PA through data dispossession of farms and farmers in South Dakota and Vermont further reflects agritech's ceaseless pursuit of profit, facilitating the capitalist class to reproduce itself and its dominance over the laboring class.

As a corollary to changing representations of reality into virtuality, technological innovation in agriculture transforms farmers into managers of precision technologies rather than laboring as producers. Although these new human-machine partnerships can make farm work more efficient and less time-consuming for more affluent farmers (Wolfert et al. 2017), advancements in precision technologies aimed at increasing automation in farm tasks and efficiency may replace or displace different types of farm labor, which often involves a process of de-skilling or re-skilling farm workers that produces inequality among other classes of farmers who are not digitally literate (Klerkx et al. 2019; Wolfert et al. 2017). PA is swiftly bifurcating agrarian labor into two groups: one possessing high digital skills to manage agricultural technologies and another group having less technical skills and is subject to employers of labor (Rotz et al. 2019a; Bernstein 2006). This process can reduce the demand for unskilled labor, including migrant, hired, and seasonal labor (Carolan 2020; Klerkx et al. 2019; Rotz et al. 2019b). For the future of farming to be sustainable, it is imperative to redesign how PA is currently formulated, where agritech has more benefits in data access and control of their farm data, helping to ensure that data can be easily accessed and owned by farmers, which can ensure that farmers can have greater financial freedom and autonomy (Rotz et al. 2019a). Transparency in how farm data is collected and used by agritech can increase farmers' autonomy as more knowledge about the production process will better inform farmers' choices on recommendations (van der Burg et al. 2019). Although farmers generate farm data, it does not guarantee they have access and control over how their data is used (Wiseman et al. 2019).

Second, our results reveal that farmers are dispossessed of their autonomy through the terms of engagement, contracts, and end-user agreements protected by intellectual property rights, which dictate how agritech relates with farmers. These new modalities of engagement avail no opportunity for farmers to negotiate the contracts and end-user agreements that guide their activities when adopting PA technologies (Carbonell 2016; Gardezi and Stock 2021; Posadas et al. 2023). When farmers do not agree to terms and contracts set by agritech firms, these technologies further lead to and contribute to the existing digital divide or exclusion of farmers who are not willing to engage because of a lack of skill sets or understanding of the terms of engagement (Rotz et al. 2019a; Eastwood et al. 2019; Posadas et al. 2023). The exclusion of some farmers may undermine agriculture's current and future sustainability objectives. Further, farmers who adopt these technologies might erode their autonomy to fix their machinery. Although farmers can seek the help of approved technicians (Fraser 2019; Jakku et al. 2019), the delay that comes with maintaining their equipment creates a pool of tech-savvy farmers who hack into computers to modify their farm machinery (Carolan 2017; Regan 2019). To ensure that hacking activities in agricultural systems are limited (Carolan 2017), there is a need to regulate the activities around the collection and use of farm data to ensure that PA meets the objectives for food security and climate change interventions. In addition to farmers in South Dakota and Vermont losing their autonomy to fix their farm machinery and production processes, farmers' social identities are also transformed by PA. FGD participants explained how PA might be reconfiguring what it means to be a good farmer – from being a data gatherer to an information validator (Gardezi and Stock 2021; Ogunyiola and Gardezi 2022).

Third, our results indicate that the introduction of PA is transforming agrarian labor in the US food system. PA can be unsettling for future and current agrarian labor in the US food systems (Erickson et al. 2018). According to the agrarian question of labor and influenced by the ideas of Bernstein (2006), the adoption of PA by farmers requires a significant amount of investment in both hardware, software, and framing recommendations generated by PA tools, which creates a social exclusion where differentiation of agrarian classes is emerging as PA serves as a tool developed by agritech for a specific type of farmer, particularly

large-scale farmers who are most likely to afford PA while inaccessible for majority of smallholder farmers. Our results show that FGD participants echo that this social exclusion is creating a consolidation and homogenization of farmland that benefits a few large-scale farmers and agritech (Bernstein 2006).

PA represents a continuation of the trend where agriculture is becoming more industrialized. The growing dependence of farmers on PA is reshaping labor dynamics, with tasks such as planting and harvesting potentially being automated due to machines' increased autonomy in decision-making and task execution, which were previously reliant on human labor. This shift has led to the commodification and exploitation of farmers' labor—blending manual and digital work—contributing to unemployment among low-skilled, migrant, and hired laborers (Bernstein 2006; Carolan 2020; Rotz et al. 2019b; Li 2010, 2011).

Similarly, our study also captures that PA has the potential to significantly impact the knowledgeability of farmers and farm workers by automating routine tasks, thus disrupting the future of agrarian labor in the US food system. Farmers and farm workers are transitioning into 'digital laborers' due to the displacement and replacement of traditional farming tasks (Klerkx et al. 2019; Rotz et al. 2019b), representing a novel accumulation strategy of agritech. Despite evolving roles, farmers are often uncompensated for extensive data collection facilitated by digital technologies (Stock & Gardezi 2021; Ogunyiola and Gardezi 2022), posing a threat to the expertise of manual laborers and further distancing them from the agrarian production process. To enhance crop production and ecological benefits through PA, we recommend establishing governance mechanisms to oversee technology development and equitable data-sharing practices between farmers and agritech. An equity-focused approach to data sharing can facilitate a more balanced redistribution of power between agritech entities and farmers.

Conclusion

PA represents a suite of novel accumulation strategies by agritech firms that wield increasing power over the political economy of US agriculture. The introduction of PA has been described by agritech and the state as the future of agriculture, capable of improving farming efficiencies in crop production and reducing the negative effects of climate change. However, the emergence of PA has far-reaching implications for dispossessing farmers' autonomy and control over agrarian production systems. In this paper, we explored two critical issues regarding the introduction of PA in the US food system: (1) *In what ways is PA dispossessing farmers of their autonomy and production processes?* and (2) *How might PA reconfigure future agrarian labor in the US food system?* We used data from FGDs in South Dakota and Vermont to answer these research questions.

Using the theoretical lens of accumulation of dispossession and the agrarian question of labor, this study concludes that PA is a strategy for different regimes of dispossession within the agrarian production system. Majorly, the digital representation of land and food production systems manifests agritech's control over big data. Through the framework of accumulation by dispossession, agritech promotes the adoption of PA among farmers, enabling the collection of data for the eventual automation of farm work, which could have a significant impact on the livelihoods of farmers. We believe that the problematics of the agrarian question of labor are still present under the emergence of PA in the food production system. We identify that PA is designed for specific kinds of farmers, specifically large-scale farmers with the financial capacity to transition to PA, creating social exclusion between agrarian classes in the food production system. We assert that PA is not only dispossessing farmers but also changing the current and future labor dynamics in the food production systems, where most farmers who adopt PA require training and skills to successfully transition to PA while manual labor is displaced or replaced by PA.

We propose that for PA to realize the proposed benefits for increased crop production against uncertain and extreme climate impacts, food system stakeholders must reconsider and redesign PA for considerations of equity and justice in data sharing to ameliorate the digital divide in farming that PA worsens. Current PA technologies give agritech firms the power to control and manipulate farm data for their sole benefit (Stone 2022; Posadas et al. 2023). The lack of transparency that comes with adopting PA undermines the potential of farm data to be collected by farmers whose experiential knowledge can augment the technological applications towards efficiency and productivity in the production system. As presently designed and implemented, the power asymmetries between agritech and farmers will continue through the dispossession of farmers' autonomy and control of production processes and the dispossession of farmers' data. The future of farming is unsustainable if PA machines alienate the farmers who cultivate farm data.

Appendix

Table 3 Codebook- implications of PA on farmers' autonomy and future agrarian labor

Code	Brief definitions	Inclusion criteria	Example
The introduction of technology	Farmer's adoption of PA	Where PA is used to describe adoption	"…the continuous innovation of agricultural technologies, such as Precision Agriculture (PA) and genetically modified seeds, exemplifies the trend of automation we have already seen. We have experienced significant automation, which is just a continuation of that trend."
Future agrarian labor	What farmers are likely to do in the future because of the introduction of PA	Statements referring to farm work in the future	"…I envision managing a fleet of robots [PA tools] or something along that line, where maybe I'm the tender truck driver moving them from field to field and managing ground truth and doing that sort of thing."
Data collection	Farmers are collecting copious amounts of data	When there is a mention of data collected by farmers or through PA technologies	"[with regards to agricultural innovations], we are right in the middle of precision agriculture; we are harvesting an enormous amount of data every day on every milking process."
Dispossession of farmers' autonomy and data	How farmers lose control of their production process	Include when statements talk about farmers' inability to control their production processes	"… double-edged sword part [of agricultural innovations].… it is beneficial to have the aggregated data for making decisions on the fly [rather than the traditional mode of decision making]."
Skills and workforce development	Farmers now collect more enormous amount of data than previously known and available on site-specific farmlands	When statements make mention of data collected by farmers	"The advancement in agricultural innovation, such as precision agriculture, will lead to a decline in the need for manual labor skills. Instead, one or two people on the farm operation will have to be proficient in mathematics and computer analysis."

Acknowledgements This research is based upon work supported by the National Science Foundation under Grant Numbers 2026431 and 2202706 and the Social Science Research Council's Data Fluencies Workshop Participant Grant, with funds provided by the Andrew W. Mellon Foundation through Simon Fraser University. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation or the Social Science Research Council.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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