



Factors affecting farmer perceived challenges towards precision agriculture

Tong Wang¹ · Hailong Jin¹ · Heidi L. Sieverding²

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Abstract

Precision Agriculture (PA) manages field heterogeneities and enables informed site-specific management. While PA helps improve farming efficiency and profitability, challenges prior to and following PA adoption can prevent many farmers from widely using it. This paper aims to understand producers' challenge perceptions using 1119 survey responses from U.S. Midwest farmers. The majority (59%) of respondents have adopted at least one PA technology, while the minority (14%) had not adopted any PA technologies. Cost (equipment and service fee), brand compatibility, and data privacy concerns topped other concerns from the average producer's point of view. Among all producers, 60% regarded PA equipment and service fee as too high, followed by 50% who viewed brand compatibility and data privacy as their major concerns. Producers at more advanced adoption stage indicated reduced concerns in most categories. Yet, there were similar concerns towards data privacy issue regardless of the adoption status. Furthermore, brand compatibility issue is more of a concern for adopters than for non-adopters. Estimation results from partial proportional odds (PPO) models show that factors that frequently affect producers' perceived challenges include adoption status, cropland acres, age, education, information sources, farming goals, soil characteristics, and region variables. Findings from this study can aid PA stakeholders in identifying target groups, tailoring future development, research, and outreach efforts, and ultimately promoting efficient PA usage on a broader scale.

Keywords Adoption · Farmer survey · Partial proportional odds model · Perceived challenges · Precision agriculture

✉ Tong Wang
tong.wang@sdstate.edu

¹ Ness School of Management & Economics, South Dakota State University, Brookings, SD 57007, USA

² Department of Civil and Environmental Engineering, South Dakota School of Mines and Technology, Rapid City, SD, USA

Introduction

Mechanization of agriculture sector promotes economies of scale but sacrifices farmers' capability to address within-field variability temporally and spatially (Finger et al., 2019; Zhang et al., 2002). The introduction of PA technologies is shifting paradigms within farming. First developed in 1980s and commercially available during the 1990s, precision agriculture (PA) allows for field management at a much finer scale by addressing heterogeneities and enabling informed site-specific management decisions (Aubert et al., 2012; Lowenberg-DeBoer, 2015; Mulla, 2013). By accounting for the spatial and temporal variability, PA contributes towards improving farming efficiency, increasing crop production, enhancing economic viability, and reducing environmental problems (Bongiovanni & Lowenberg-DeBoer, 2004; Finger et al., 2019; Fountas et al., 2005).

Precision agriculture encompasses a wide array of technologies. Based on the level of skills and time required, PA technologies can be divided into two broad categories, embodied-knowledge and information-intensive technologies (Griffin et al., 2004; Miller et al., 2019). While the former (such as auto-steer or yield monitors) requires little additional skills, the latter (such as site-specific management) requires technological skills or training. Information intensive technologies are further divided into diagnostic and application technologies (Nowak, 2021). Diagnostic technologies gather farm information at various scales, and application technologies, comprising variable rate (VR) fertilizer use, irrigation, pesticide use and seeding, enable site-specific management responses using the gathered information. Precision technologies have both private and public benefits, including improved equipment use efficiency, increased yield quantity and quality, decreased fuel consumption, reduced greenhouse gas emissions, and improved water quality due to more efficient fertilizer and pesticide use (Griffin et al., 2018). Nevertheless, the adoption rates of some PA technologies, especially those of application technologies, remained low based on reviews of publicly available data (Lowenberg-DeBoer & Erickson, 2019).

Challenges faced by producers, if not addressed, could constrain farmers' ability to adopt and efficiently use PA technologies. Shortly after PA technologies became commercially available to the farmers, Wiebold et al. (1998) identified the main concerns raised by adopters and non-adopters in North Central U.S., which included high cost, lack of technical infrastructure, lack of information for format compatibility and soil suitability, data interpretation difficulty, and lack of evidence on PA benefits. Based on a farmer survey in western Canada, Steele (2017) found the top four barriers towards PA adoption were price, internet speeds, lack of knowledgeable people, and continuously evolving technology. Through examining public thoughts via machinery-learning based social media analytics tool, a more recent study by Ofori and El-Gayar (2021) found the most common challenges for PA were cost, complexity, data security, and privacy.

Besides farmers' perspectives, a few papers have also documented the perspectives of researchers and dealers about their understanding of PA related challenges faced by producers. Among these, Mintert et al. (2016) brought up challenges on lack of knowledge and expertise with field input recommendations and appropriate size of management zones and soil sampling zones. Through a PA dealer survey, Mitchell et al. (2017) found that dealers perceive farm income constraints and high technology costs as two major barriers that prevent their consumers from using or expanding their precision services. Furthermore, Mitchell et al. (2020) identified three most important barriers rated by agricultural retailers as financial pressure, high PA costs (equipment and service fee), and lack of confidence towards agronomic recommendations based on PA data.

Different farmers could also interpret challenges in distinct ways. For example, when compared with the younger generation, older farmers tend to perceive PA usage as more challenging as they typically have steeper learning curves, less likely to make large initial investment, and less likely to use internet for farming purposes (Wiebold et al., 1998). Highly educated farmers generally have greater ability to decipher new information, and therefore are more likely to adopt information intensive technologies (Larson et al., 2008; Paxton et al., 2011; Weersink et al., 2018). In addition, farm size likely plays a role on farmer perceived cost challenge as larger farms exhibit greater capacity and are in better positions to absorb the fixed costs (Daberkow & McBride, 2000; Lambert et al., 2015; Robertson et al., 2012; Tey & Brindal, 2012; Watcharaanantapong et al., 2014). Furthermore, larger farms often have employee(s) responsible for PA technologies to ensure successful application, yet smaller farms typically do not have such specialization in human resources and view their farm size as an important barrier to precision farming (Balogh et al., 2021; Reichardt et al., 2009). Farm resource availability also likely affects the perception of cost challenges, and therefore, may have a significant impact on PA adoption decisions (Aubert et al., 2012).

While previous research has ranked potential barriers that affected PA adoption decisions, no study has investigated how these challenges may vary for adopters at different adoption stages, and how non-adopters' views on PA challenges may differ from those of adopters. Furthermore, none of the existing studies has analyzed factors that could potentially affect producer views towards PA challenges. This paper intends to fill in these gaps using farmer survey information from Midwestern U.S in 2021. The main objectives of this paper are: (1) gaining insights towards PA related challenges by comparing views of producers under different PA adoption status; and (2) identifying potential factors that significantly affect producers' perceived challenges. Survey sample for this study spans four U.S. Midwest states and covers farms under different PA adoption stages and regions with diversified soil, climate, and infrastructure conditions, which enables a better understanding of PA challenges faced by a diverse profile of producers and factors that lessen or aggravate those challenges.

Challenges faced by farmers towards PA technologies

The adoption of PA technologies involves additional costs, such as initial investment cost, annual subscription costs, maintenance, and operating costs (Griffin et al., 2018). In a meta-analysis of PA adoption, perceived profitability was found to be a significant predictor of adoption across studies (Tey & Brindal, 2022). Yet many farmers considered initial PA costs as too high when compared with returns (Pedersen & Lind, 2017; Weersink et al., 2018). The high upfront cost could inhibit adoption, especially for financially constrained farmers. Financial factors also pose major constraints to most of the innovative firms (Balogh et al., 2021).

Data ownership and privacy concerns pose challenges for farmers. When PA practices were first introduced, data generated belonged to farmers. With the launching of the big data era, data are aggregated across many farms and can be used in analyses, services, and products created without farmer knowledge (Sykuta, 2016). This implies farmers could be in a disadvantageous position if they disclose too much information to technology providers (Linsner et al., 2021). Shang et al. (2021) also highlighted farmer concerns about potential misuse of digitally gathered data by commercial service providers. While around

40% farmers trusted sharing data with university researchers, cooperatives, and relatives, almost a quarter (23%) of farmers indicated that they trusted their data with no one (Castle et al., 2015). As use of PA equipment or services often requires producers to agree with sharing data, data privacy is a valid concern.

The compatibility of PA technology with existing resources affects ease of use, which in turn affects PA adoption. Compatibility, either among different manufacturer brands, or between hardware and software, could also be a concern to producers (Pedersen & Lind, 2017; Reichardt et al., 2009). Technology not compatible with current practices, equipment or existing software will pose additional challenges for farmers to adopt, especially for operations that require expensive equipment and specialized procedures (Aubert et al., 2012).

A time commitment is also required to learn PA technologies, especially for information-intensive technologies that require hidden costs in terms of education and data collection (Aubert et al., 2012; Griffin et al., 2018; Reichardt et al., 2009; Vecchio et al., 2020). Farm operators, with other more prioritized tasks, generally do not have sufficient time to learn all the necessary skills (Mitchell et al., 2020). Thus, adoption is typically slow for complex technologies, as complexity alone can pose a real barrier, especially if there is limited ‘know-how’ support (Pedersen & Lind, 2017; Vecchio et al., 2020). The perceived ease of use, therefore, plays a role and ‘prohibitively steep’ learning curves will inhibit PA adoption (Sassenrath et al., 2008).

Knowledge affects farmers’ adoption decisions. Successful handling of PA machinery and software hinges on good information service and training (Reichardt et al., 2009). Many farmers face difficulties in analyzing and interpreting data, which hinders use of data and management decisions based on them (Sørensen et al., 2002; Fountas et al., 2005; Reichardt et al., 2009; Castle et al., 2015; Weersink et al., 2018). Additionally, adoption can be constrained by poor user experience, limited access to information and technical assistance (Zhang et al., 2021). Moreover, demonstration and exhibition events significantly affect farmers’ adoption decisions (Tamirat et al., 2018). Farmers need to see successful PA applications on lands like theirs to understand benefits (Balogh et al., 2021). Limited broadband connectivity in some rural areas also poses a barrier to PA adoption and restrict the benefits of PA technologies (Whitacre et al., 2014; Steele, 2017; Griffin et al., 2018; Weersink et al., 2018).

Survey description

From July to September in 2021, a mail survey was conducted by researchers in four U.S. Midwestern states, namely North Dakota (ND), South Dakota (SD), Minnesota (MN) and Nebraska (NE). For each state, counties intensive in corn and soybean production were selected. The number of farms selected for each county was proportional to the number of total eligible corn farmers in that county. Together, 1500 farmers were randomly selected for each state, with 6000 producers in total.

Based on the modified Tailored Design Method, the selected producers were contacted up to four times (Dillman et al., 2014). Specifically, farmers were mailed an advanced letter, a paper questionnaire, a reminder postcard and a second copy of the paper questionnaire for waves 1 to 4 respectively. To enhance survey response rates, a \$2 bill was enclosed with the advance letter to enhance response rates. Out of 6000 addresses, 101 were non-deliverable and 426 were no longer farming. Out of 5473 eligible addresses,

1119 responses were received with the response rate of 20.4%. Survey responses were generally well distributed across the targeted region, with only a handful of selected counties not represented, predominantly in the northern portion of the surveyed area (Fig. 1).

Data description

In the survey, producers were asked about their views towards potential challenges posed by PA technologies. Together, 11 potential challenges were presented, which could be divided into four categories: (1) cost concerns; (2) technology concerns; (3) complexity concerns; and (4) infrastructure and support concerns (Fig. 2). Under cost concerns, two statements included were ‘cost of PA equipment too high’ (abbreviated as ‘*Equipment*’. Variable abbreviations are also provided for other challenges in bracket following each statement) and ‘cost of PA service fee too high’ (*Service*). For technology concerns, farmers’ potential concerns about technology limitations were included, which are ‘lack of compatibility among different brands’ (*Compatibility*) and ‘concerned over data privacy’ (*Privacy*). Two statements included in the complexity concern category are ‘not sure how to use PA data effectively’ (*Data*) and ‘PA technology too time-consuming to learn’ (*Time*). The rest five challenges are infrastructure/support concerns, namely ‘Not sure whether soil conditions on my farm will benefit from PA’ (*Soil*), ‘Limited information about the best PA technologies for my farm/region’ (*Information*), ‘Limited on-farm research and demonstration’ (*Research*), ‘Not confident in prescription maps and agronomic recommendations’ (*Map*) and ‘Lack of strong, reliable internet connectivity’ (*Internet*). For each statement, producers could indicate their views by choosing one of the five options (1 = ‘strongly disagree’, 2 = ‘disagree’, 3 = ‘neutral’, 4 = ‘agree’ and 5 = ‘strongly agree’). Together, 11 perceived challenges as dependent variables developed, as described in Fig. 2.

The explanatory variables that might affect producer perceived challenges are divided into six categories, namely farm characteristics and management, farmer characteristics, management goal, information sources, soil characteristics, and state variables

Fig. 1 Counties in North Dakota (ND), South Dakota (SD), Nebraska (NE), and Minnesota (MN) with survey responses



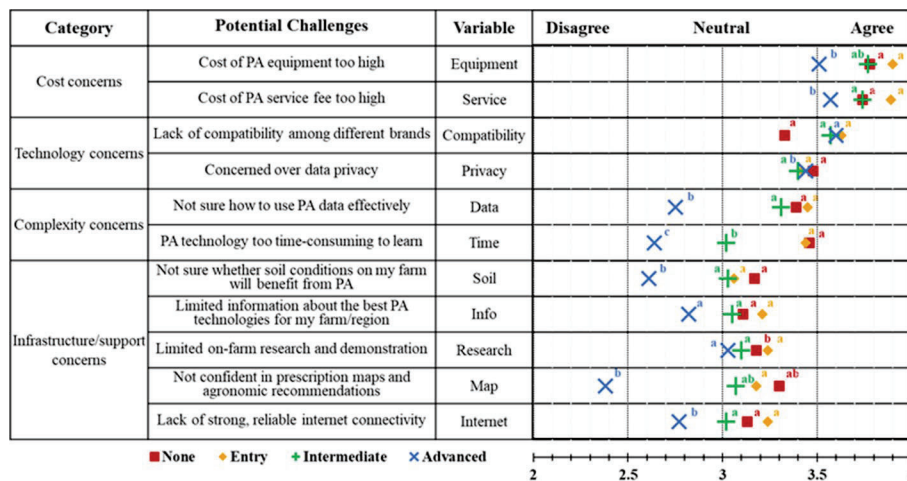


Fig. 2 Average ratings of challenges in four different categories (from 1 = “strongly disagree” to 5 = “strongly agree”) by adoption status (none to advanced). Note: Letters are used to denote Duncan’s multiple range test results, where the same letter implies no statistically significant difference at $p < 0.05$

(Table 1). Among the farm characteristics and management category, adoption status, cropland area, ownership, and liability were included. To capture the effect of PA adoption status on perceived challenges, producers were grouped based on their usage status of PA technologies. Due to the variety of PA technologies, producers cannot be simply grouped into adopters and non-adopters of PA technologies. Instead, producers were categorized into four different groups, as demonstrated in Table 2. These are (1) non-adopters, which refers to producers who have not adopted any of the PA technologies; (2) entry-level adopters, who adopted at least one of the georeferencing technologies, i.e., global positioning system (GPS) and GNSS systems; (3) intermediate-level adopters, which refers to those on top of geo-referencing technologies, have adopted at least one of the diagnostic technologies, such as sensors, satellite images, unmanned aerial vehicles (UAVs), and yield monitors; and (4) advanced adopters, which adopted technologies from all three categories of technologies, i.e., geo-referencing, diagnostic, and application technologies. It is hypothesized that as producers get more advanced in the adoption stage, they will be more established and knowledgeable about the technology and therefore will likely encounter less challenges for most of the categories such as cost and complexity concerns.

Farm size and land tenure are also included as explanatory variables. Specially, cropland area was included to understand whether larger farm size may result in lesser degrees of perceived challenge, especially when it comes to the cost concerns. Previous literature has demonstrated a positive relationship between farm size and PA adoption status (Shang et al., 2021; Tamirat et al., 2018), yet the effect of farm size on perceived PA challenges has not been studied. Land tenure was included to see whether farmers perceive greater challenges towards PA technologies on rented land. Liability ratio, as calculated by total debt divided by total assets value, was also included, mainly to test the hypothesis that due to the investment requirement of PA technologies, the producers with a high liability may perceive the cost related issues as more challenging. It is a discrete variable, with 1 = ‘0%’, 2 = ‘1–20%’, 3 = ‘21–40%’, 4 = ‘41–60%’, 5 = ‘61–80%’ and 6 = ‘More than 80%’.

Table 1 Description of explanatory variables used in the partial proportional odds (PPO) models

Category	Variable	Variable type	Variable description
Farm characteristics and management	Adoption status	Discrete	Adoption status of precision agriculture technologies (0 = 'non-adopter'; 1 = 'entry adopter'; 2 = 'intermediate adopter'; 3 = 'advanced adopter')
	Cropland area	Continuous	Total area of cropland (in 1000 acres)
	Tenure	Continuous	Percentage of crop acres that is owned (owned acres/total acres)
	Liability	Discrete	Total debt divided by total asset value (1 = '0%'; 2 = '1–20%'; 3 = '21–40%'; 4 = '41–60%'; 5 = '61–80%'; 6 = 'More than 80%')
Farmer characteristics	Age	Continuous	Farmer age
	Education	Discrete	Highest education level completed (1 = 'High school or less' or 'Some college/technical school'; 2 = '4-year college degree' or 'Advanced degree')
Management goal	Ag Major	Discrete	Whether completed an ag major in college or not (1 = yes, 0 = no)
	Technology	Discrete	Importance of "keeping pace with new technology" as a farm management goal (1 = 'Not important'; 2 = 'Slightly important'; 3 = 'Somewhat important'; 4 = 'Very important'; 5 = 'Extremely Important')
	Kids	Discrete	Importance of "getting kids into farming" in PA adoption decisions (1 = 'Not important'; 2 = 'Slightly important'; 3 = 'Somewhat important'; 4 = 'Very important'; 5 = 'Extremely Important')
Information sources	Extension	Discrete	Importance of university extension when making PA decisions (1 = 'Not important'; 2 = 'Slightly important'; 3 = 'Somewhat important'; 4 = 'Very important'; 5 = 'Extremely Important')
	Machinery dealers	Discrete	Importance of machinery dealers when making PA decisions (1 = 'Not important'; 2 = 'Slightly important'; 3 = 'Somewhat important'; 4 = 'Very important'; 5 = 'Extremely Important')
Soil characteristics	HEL	Discrete	Percentage of cropland that is highly erodible land (HEL) (1 = '0%'; 2 = '1–5%'; 3 = '6–10%'; 4 = '11–20%'; 5 = '21–30%'; 6 = 'More than 30%')
	Saline/sodic	Discrete	Percentage of cropland that has saline or sodic conditions (1 = '0%'; 2 = '1–5%'; 3 = '6–10%'; 4 = '11–20%'; 5 = '21–30%'; 6 = 'More than 30%')
	Slope	Continuous	Slope of the field (degree)
State	LCC12	Continuous	Land Capability Class 1 and 2
	ND	Discrete	1 = farm located in ND, 0 otherwise
	NE	Discrete	1 = farm located in NE, 0 otherwise
	MN	Discrete	1 = farm located in MN, 0 otherwise

Table 2 Producers groupings based on adoption status of precision agriculture technologies

Technologies			Adoption status	Frequency	Percent (%)
Georeferencing	Diagnostic	Application			
			Non-adopter	133	13.9
X			Entry adopter	65	6.8
X	X		Intermediate adopter	200	20.8
X	X	X	Advanced adopter	562	58.5

Three variables were included under the farmer characteristic category, namely age, education, and agricultural major in college. Age could play a twofold role in perceived challenges. On one hand, younger farmers are generally more accustomed to and confident in learning new technologies, thereby they perceive less challenge regarding the complexity of PA technology.

On the other hand, younger farmers typically have not accumulated sufficient financial resources to afford the expensive PA technologies, so they are likely to view PA technology as more challenging when it comes to equipment and service costs. Education is expected to be negatively related to perceived challenges, especially when it comes to those issues under the complexity category, as farmers with higher level of education are more likely to possess the skills to learn and efficiently use PA technologies. In addition to general education, agriculture related major (e.g., agronomy, animal science, agricultural business) in college was included to understand whether specialized education in the agriculture related area equips producers with more expertise about the crop production and related skills, thus reducing the corresponding challenges associated with PA usage.

Moreover, management goals could also affect farmers' perceived challenges. Producers will likely express more concerns towards PA if they demonstrate less interest or motivation towards using the technology, and vice versa. For example, if farmers view 'keeping pace with new technology' as one of their most important farming goals, then it is likely that they do not perceive major challenges associated with PA due to their inner desire to learn and use the new technologies. On the contrary, those who think PA adoption benefits them in a way that it helps attract their kids back to the farm may perceive greater challenges as they may not be fans of PA technologies themselves.

External information sources and technical assistance may also play an important role in reducing or eliminating perceived PA challenges, regarding barriers to data analysis, interpretation, and recommendations (Robertson et al., 2012; Tey & Brindal, 2022). The role of university extension and machinery dealers, two potential sources that could help farmers better utilize PA technologies, were examined in this paper. Extension serves as an intermediary between researchers and producers and provides public goods, which include reducing technology implementation uncertainty and overcoming barriers to adoption for precision farming (Eastwood et al., 2017). Similarly, machinery dealers could also be a source of information when it comes to issues such as compatibility between components and brands (Andrade-Sanchez & Heun, 2010). Therefore, farmers who value more about those information sources in their decision making are likely to perceive less challenges, especially in the categories of complexity and support issues.

The effectiveness of the PA technologies could vary across different soil quality and variability, which in turn could affect the perceived challenges for PA. For example, fields with higher spatial variability will be more likely to gain from the adoption of VR technologies,

which allows variation in timing and application rates (Khanna, 2001). Therefore, four variables were included to capture the soil characteristics (Table 1). Among those, two of them are farmers' own thoughts about percentages of their cropland that is under highly erodible land (HEL), and percentages that has saline/sodic conditions. Furthermore, farmer survey responses were complemented with soil information from gridded Soil Survey Geographic (gSSURGO) and the Soil Survey Geographic (SSURGO) databases. The latitude and longitude coordinates for the largest crop land unit (CLU) associated with each farm were purchased, and based on which, the average soil variable information was calculated for the 1-km buffer of each CLU. Among the publicly available soil variables, average land slope was used to capture the degree of variability in the terrain, and the percentage of soil under land capability class (LCC) I and II to indicate land suitability for cultivated crops. In addition, producers' challenge perception could vary by region and states, potentially due to the differing trust in information sources, various stage of support and infrastructure development. To capture the state and regional effects, three states, ND, NE, and MN were used as dummy variables with SD serving as a baseline state.

Model description

The empirical model aims to locate potential variables that significantly affect producers' perceived challenges in four different categories, as described in Fig. 3. Five options were provided in the survey so that towards each of the listed challenges producers could express their degrees of agreement, which are 'strongly disagree', 'disagree', 'neutral', 'agree' and 'strongly agree'. As demonstrated in Fig. 3, only few respondents (in most cases less than

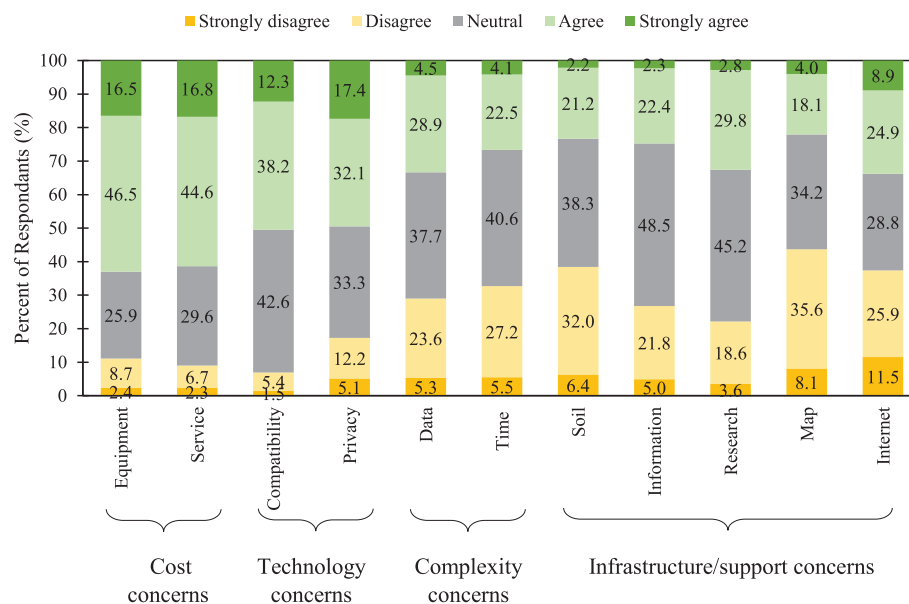


Fig. 3 Producers' rated challenges towards precision agriculture adoption and usage. Note: The total number of responses for the listed challenges range from 1071 to 1077

5%) selected ‘strongly disagree’ for the cost and technology concerns, and few respondents (in most cases less than 5%) selected ‘strongly agree’ for the complexity and support concerns. Therefore, the ‘strongly disagree’ with the ‘disagree’ category were combined, as were the ‘strongly agree’ with the ‘agree’ category. In the regression model, the dependent variables take three different values, 1 = ‘disagree or strongly disagree’, 2 = ‘neutral’, and 3 = ‘agree or strongly agree’.

Due to the ordinal nature of the responses, the ordered logit model is the appropriate modeling choice. According to Williams (2006), a generalized ordinal logit (GOL) model is specified as follows:

$$P(Y_i > j) = g(X\beta_j) = \frac{\exp(\alpha_j + X_i\beta_j)}{1 + \exp(\alpha_j + X_i\beta_j)} \quad j \in \{1, 2\}. \quad (1)$$

As each challenge variable takes three different values, The GOL model has two sets of coefficients, denoted by β_j ($j \in \{1, 2\}$). The parameter α_j denotes the model intercepts, and X_i stands for the vector of explanatory variables. The Brant test was used to determine whether the Proportional Odds (PO) assumption held for each of the individual explanatory variables, i.e., coefficients are the same across different values of j , or $\beta_j = \beta$ for $j \in \{1, 2\}$. A series of Wald tests were conducted to check whether PO assumptions hold for 18 explanatory variables. Following Bonferroni correction criterion, $p\text{-value} = 0.05/18 = 0.0028$ was used instead of a $p\text{-value}$ of 0.05. For all 11 models being estimated, the PO assumptions are violated by one or more variables. Therefore, for all 11 challenges, partial proportional odds (PPO) models were used, which allows one or more coefficients to differ where PO assumption is violated, while the others are kept the same. Following Williams (2016), the PPO model can be specified as:

$$P(Y_i > j) = \frac{\exp(\alpha_j + X_i\beta + Z_i\beta_j)}{1 + \exp(\alpha_j + X_i\beta + Z_i\beta_j)} \quad j \in \{1, 2\}. \quad (2)$$

For a PPO model, the explanatory variables can be divided into two categories: (1) X_i stands for the vector of variables that meet the PO assumption for the challenge i model and therefore, the same coefficient β is estimated across different values of j ; (2) Z_i represents the vector of explanatory variables that violate the PO assumption for challenge i model and have different coefficients estimated for different values of j . The PPO models were estimated using Stata Software (version 17.1, StataCorp, College Station, TX, USA).

Results and discussion

Perceptions of different challenges

Among the four categories of potential concerns, cost was ranked by most producers as their top concern, followed by technology concerns. Of all producers, over 60% of producers regarded PA equipment and service fee as too high (either agree or strongly agree), and about 50% of producers listed lack of compatibility among brands and data privacy as their concerns (Fig. 1). Among those, 17.4% of producers strongly agreed that data privacy posed a concern for them, which ranked the highest among all the potential challenges, followed by PA service cost (16.8%) and equipment cost (16.5%).

The cost concerns identified in this paper is consistent with that of Steele (2017), which found the top PA barrier was price, posing a significant barrier for 40.2% and a barrier for 36.2% of farmers. Similarly, Mitchell et al. (2020) found that financial pressure and high cost of PA services are the top two concerns rated by agri-retailers about their consumers. However, data privacy and brand compatibility concerns have not been identified by other research as one of the top concerns, except for the study that is based on social media where public thoughts were examined (Ofori and El-Gayar, 2021). This suggests that challenges faced by farmers are evolving along with technological development. In this regard, dealers/researchers' views may differ from those of farmers.

Compared to the cost and technology concerns, fewer producers showed agreement with complexity concerns. Only less than 5% of producers indicated strong agreement towards the statement 'not sure how to use PA data effectively', and 'PA technology too time consuming to learn', with another 28.9% and 22.5% of producers showing agreement towards the two statements, respectively. Between the two complexity concerns, more producers showed concerns towards the effective use of PA data, rather than the time-consuming side of PA technology.

Similarly, for the support and infrastructure concerns, less than 5% of respondents showed strong agreement, except for the internet connectivity concern, with which 8.9% strongly agreed. The internet posed a constraint for one third of the respondents, who either agreed or strongly agreed that there is a lack of strong, reliable internet connectivity for them to use PA efficiently. Respondents' opinion towards internet connectivity concern falls evenly under the 'disagree', 'neutral' and 'agree' categories, which indicated disparity in internet connection conditions across the study area. Among the other potential concerns that fall into the support and infrastructure category, over 30% either agreed or strongly agreed with the limitation in on-farm research and demonstration, potentially hampering them from utilizing PA.

Of all the provided concerns, least producers indicated agreement with concerns towards land suitability and expert opinions. In this regard, most producers (43.7%) indicated disagreement (either strongly disagree or disagree) towards 'not confident in prescription maps and agronomic recommendations', followed by 38.4% of producers disagreeing with 'not sure whether soil conditions on my farm will benefit from PA'. In comparison, least producers (6.9%) disagreed with the statement 'lack of compatibility among different brands', followed by 9.0% of those disagreeing with 'cost of PA service fee too high'.

Comparison of perceived challenges across different adoption stages

Only 13.9% of the survey respondents indicated that they have not adopted any of the PA technologies (Table 2). Among the adopters, many have advanced from the entry level to the intermediate level, and the majority have made it to the advanced level. To qualify for the intermediate and advanced adopters, producers need to adopt at least one of the informative intensive technologies.

Results of Fig. 2 indicate that as the adoption level increases, generally the perceived challenge level will decrease. For example, the advanced adopters perceived significantly less challenge in the cost, complexity, and infrastructure/support concerns. The only exception occurs with the technology related concerns, as producers with different adoption status showed similar concerns towards data privacy, and adopters at different adoption stages all expressed more agreement towards the compatibility concerns than the non-adopters.

This is reasonable as non-adopters have no experience using PA technologies, therefore, many of them do not foresee the type of issues that only become fully revealed after usage.

The top three challenges faced by different producer groups differ. The top two challenges for non-adopters, entry- and intermediate-adopters are high equipment and service cost, followed by data privacy as the third top challenge for non-adopters, and brand compatibility as the third top challenge for the other two groups. For the advanced-adopter group, the top challenge is lack of compatibility, followed by high service and equipment cost. The least important challenges also differ among different groups. For non-adopters of any PA technology, the top three least concerned issues are information, internet, and soil, all of which belong to the infrastructure/support issues. Similarly, entry-adopters also demonstrated the least concerns towards the infrastructure/support issues. This suggests that more input towards the local demonstration, information dissemination, and internet connection areas are unlikely to address the major concerns faced by non- and entry-adopters, as they are more concerned by the cost.

In comparison to the non- and entry-adopters, the intermediate and advanced adopters treated ‘PA technology too time-consuming to learn’ as one of three least important challenges. Effective utilization of PA data is among the top five challenges for three groups, except for the advanced one. This indicates that for producers to invest in application technologies, they need to be confident with the effective use of the gathered PA data.

Summary statistics of the explanatory variables

Table 3 presents the summary statistics for the explanatory variables included in the PPO models. Adoption status varies from 0 = ‘non-adopter’ to 3 = ‘advanced adopter’. A mean

Table 3 Summary statistics of explanatory variables used in the logit regression models

Category	Variable	N	Mean	Std dev	Minimum	Maximum
Farm characteristics and management	Adoption status	961	2.241	1.073	0	3
	Cropland area	1056	1.426	1.608	0.002	16
	Ownership	1056	0.528	0.329	0	1
	Liability	1008	2.383	1.082	1	6
Farmer characteristics	Age	1078	58.949	13.017	20	95
	Education	1095	1.311	0.463	1	2
	Ag major	1090	0.283	0.450	0	1
Personal goal	Technology	1083	3.253	0.956	1	5
	Kids	1083	3.440	1.252	1	5
Information sources	Extension	1067	2.636	1.178	1	5
	Machinery dealers	1074	3.130	1.246	1	5
Farm soil characteristics	Highly erodible land	1077	2.316	1.554	1	6
	Saline/sodic	1034	2.001	1.159	1	6
	Slope	1118	2.743	1.785	0	15.3
	Land capability class 1 or 2	1118	0.725	0.258	0	1
State	ND	1119	0.198	0.399	0	1
	NE	1119	0.231	0.421	0	1
	MN	1119	0.312	0.463	0	1

value of 2.241 indicates that on average, the adoption status was between the intermediate and advanced stage. The acres of cropland averaged 1426 acres, among which an average of 52.8% of the land was owned. The average liability of each farm was 2.383, which lied between the ranges of 2 = '1–20%' and 3 = '21–40%'.

The average age of producers was 59 years, and their education level was, on average, 1.311, which means that 31% of producers had 4-year college or more advanced degrees. Of all respondents, 28.3% indicated that they had completed an agricultural major in college, such as agronomy, animal science and agricultural business. When it comes to the personal goals, the importance of goals 'keeping pace with new technology' and 'getting kids into farming' were rated as 3.253 and 3.440 respectively, both between the 'somewhat important' and 'very important' categories, yet on average the latter goal was regarded as slightly more important than the former.

On the importance of information sources, the rating for university extension was 2.636, which exceeded the 'slight important' category, but has not quite reached the 'somewhat important' category. In comparison, the importance of machinery dealers was rated as 3.130, slightly greater than the 'somewhat important' category. This indicates that compared with university extension, producers regarded machinery dealers as a more valuable information source when making PA usage decisions.

Within a 1-km radius of the producers' largest CLU, 72.5% of the soil was under LCC I and II. The slopes of the field vary between 0 and 15.3 with an average slope of 2.743 degrees. This indicates most of the fields operated by the survey respondents were suitable for crop cultivation purposes. According to producers' knowledge, the percentage of land under HEL and saline/sodic conditions were 2.316 and 2.001 respectively, both slightly above the '1–5%' category. Compared to the saline/sodic land conditions, more land is subject to the erodibility concerns. The mean values for the state variables indicate that among the 1119 respondents, 19.8%, 23.1% and 31.2% were from ND, NE and MN respectively, and the rest 25.9% was from SD.

PPO model estimates for factors affecting PA challenges faced by farmers

Supplementary tables S1 to S3 demonstrate the PPO model estimation results for the 11 challenges under four different categories. Note that the observation numbers for the 11 regressions (734–737) differ from the total survey responses (1119) due to the missing values. It is commonplace for survey responses to have one or more variables not filled by respondents as their answers are not mandatory. Among the 18 explanatory variables listed in Table 3, adoption status has the lowest response rate for a single question, which is 86%, while all other variables have response rate of more than 90%. Yet, the percentage of the responses included in the analysis is much lower at approximately 66%; this is because multiple variables are included in each model. As the number of variables included in the model increases, the completion rate decreases.

To better understand the nature of dropped observations, a series of t-test analyses between the complete and incomplete answer groups were carried out with results presented in Table 4. Compared to farmers who completed all questions, those who provided partial answers were on average, older and less educated at a statistically significance level of 1%. Meanwhile, they were more likely to live in southern and eastern portion of the studied region, as illustrated by their average latitude and longitude. State wise, ND farmers were less likely to have skipped some questions, whereas MN farmers were more likely.

Table 4 Comparison between respondents who provided complete answers vs. those who provided incomplete answers

Variables	Complete answers	Incomplete answers	Sig-nificance level
Age	56.977	63.175	***
Education	1.344	1.244	***
Slope	2.853	2.686	
LCC12	0.727	0.723	
Latitude	44.243	43.926	**
Longitude	− 97.054	− 96.764	***
SD	0.260	0.258	
ND	0.226	0.146	***
NE	0.253	0.219	
MN	0.295	0.344	*

*, **, and *** represent $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively based on t-test

Yet the land quality (as indicated by slope and LCC I & II) demonstrated no statistical differences between the two groups of farmers.

Tables 5, 6 and 7 present the marginal effects for cost, technology and complexity challenge categories, respectively, while marginal effects for support and infrastructure

Table 5 Marginal effects for cost challenges faced by farmers towards precision agriculture

Variable	Equipment			Service		
	Disagree	Neutral	Agree	Disagree	Neutral	Agree
Adoption status	<i>0.096***</i>	<i>− 0.061**</i>	<i>− 0.034</i>	<i>0.084***</i>	<i>− 0.057**</i>	<i>− 0.027</i>
Cropland area	<i>0.022***</i>	<i>− 0.016*</i>	<i>− 0.006</i>	<i>0.022***</i>	<i>− 0.028***</i>	<i>0.006</i>
Ownership	<i>− 0.013</i>	<i>− 0.018</i>	<i>0.032</i>	<i>− 0.004</i>	<i>− 0.008</i>	<i>0.012</i>
Liability	<i>− 0.011</i>	<i>− 0.014</i>	<i>0.025</i>	<i>− 0.002</i>	<i>− 0.005</i>	<i>0.007</i>
Age	<i>0.001</i>	<i>0.001</i>	<i>− 0.002</i>	<i>0.001</i>	<i>0.002</i>	<i>− 0.002</i>
Education	<i>0.016</i>	<i>0.022</i>	<i>− 0.038</i>	<i>0.026*</i>	<i>0.052*</i>	<i>− 0.078*</i>
Ag Major	<i>0.013</i>	<i>0.018</i>	<i>− 0.032</i>	<i>− 0.002</i>	<i>− 0.004</i>	<i>0.006</i>
Technology	<i>0.028***</i>	<i>0.038***</i>	<i>− 0.066***</i>	<i>0.017**</i>	<i>0.034**</i>	<i>− 0.051**</i>
Kids	<i>− 0.014**</i>	<i>− 0.019**</i>	<i>0.034**</i>	<i>− 0.015***</i>	<i>− 0.029***</i>	<i>0.044***</i>
Extension	<i>− 0.019**</i>	<i>− 0.025***</i>	<i>0.044***</i>	<i>− 0.007</i>	<i>− 0.015</i>	<i>0.022</i>
Machinery dealers	<i>0.000</i>	<i>0.000</i>	<i>0.000</i>	<i>0.003</i>	<i>0.005</i>	<i>− 0.008</i>
HEL	<i>− 0.006</i>	<i>− 0.008</i>	<i>0.014</i>	<i>− 0.007</i>	<i>− 0.014</i>	<i>0.022</i>
Saline/sodic	<i>− 0.011</i>	<i>− 0.015</i>	<i>0.026</i>	<i>− 0.009</i>	<i>− 0.018</i>	<i>0.026</i>
Slope	<i>0.003</i>	<i>0.005</i>	<i>− 0.008</i>	<i>− 0.001</i>	<i>− 0.001</i>	<i>0.002</i>
LCC12	<i>0.019</i>	<i>0.026</i>	<i>− 0.046</i>	<i>− 0.011</i>	<i>− 0.023</i>	<i>0.035</i>
ND	<i>0.006</i>	<i>0.009</i>	<i>− 0.015</i>	<i>− 0.001</i>	<i>− 0.003</i>	<i>0.004</i>
NE	<i>− 0.014</i>	<i>− 0.018</i>	<i>0.032</i>	<i>− 0.028</i>	<i>− 0.056</i>	<i>0.084</i>
MN	<i>− 0.010</i>	<i>− 0.014</i>	<i>0.024</i>	<i>0.004</i>	<i>0.008</i>	<i>− 0.013</i>

Italics indicate statistically significant variables, where ***, **, and * represent $p \leq 0.01$, $p \leq 0.05$ and $p \leq 0.10$, respectively

Table 6 Marginal effects for technology challenges faced by farmers towards precision agriculture

Variable	Compatibility			Privacy		
	Disagree	Neutral	Agree	Disagree	Neutral	Agree
Adoption status	<i>0.105***</i>	<i>− 0.129***</i>	0.024	<i>0.053***</i>	<i>− 0.078***</i>	0.025
Cropland area	<i>0.008*</i>	− 0.011	0.003	0.000	0.000	− 0.001
Ownership	− 0.029	− 0.080	0.109*	0.007	0.005	− 0.011
Liability	− 0.011	0.005	0.006	0.004	0.003	− 0.007
Age	− 0.001	<i>0.003*</i>	− 0.002	<i>− 0.003**</i>	<i>0.003**</i>	0.000
Education	− 0.008	− 0.032	0.040	− 0.008	− 0.006	0.014
Ag Major	− 0.003	0.011	− 0.008	0.026	0.017	− 0.043
Technology	<i>0.021*</i>	− 0.023	0.002	0.007	0.005	− 0.012
Kids	− 0.007	− 0.016	0.023	<i>− 0.033***</i>	<i>− 0.022***</i>	<i>0.055***</i>
Extension	0.000	− 0.029	0.029	− 0.012	− 0.008	0.020
Machinery dealers	− 0.005	<i>− 0.030*</i>	<i>0.036*</i>	0.015	0.010	− 0.025
HEL	− 0.002	− 0.022	<i>0.024*</i>	− 0.006	− 0.004	0.010
Saline/sodic	<i>− 0.025**</i>	<i>− 0.031*</i>	<i>0.056***</i>	− 0.005	− 0.003	0.008
Slope	− 0.002	− 0.002	0.005	0.008	0.005	− 0.013
LCC12	<i>− 0.081*</i>	− 0.076	<i>0.157*</i>	0.026	0.018	− 0.044
ND	− 0.008	− 0.038	0.046	0.022	0.015	− 0.037
NE	− 0.016	<i>− 0.138**</i>	<i>0.155***</i>	0.026	0.018	− 0.044
MN	0.025	<i>− 0.086*</i>	0.061	− 0.005	− 0.003	0.008

Italics indicate statistically significant variables, where ***, **, and * represent $p \leq 0.01$, $p \leq 0.05$ and $p \leq 0.10$, respectively

categories are presented in Tables 8 and 9. When the adoption status increases by 1 unit on a 0–3 scale, producers are 9.6% and 8.4% more likely to disagree, while 6.1% and 5.7% less likely to be neutral towards the statements ‘cost of PA equipment too high’ and ‘cost of PA service fee too high’, respectively (Table 5). It is likely that more experienced producers perceive reduced challenges. On the other hand, perceived challenges may also affect producers’ adoption decisions in that some challenges such as data use challenge could prevent producers from advancing to the next stage. Among the listed marginal effects for the cost and technology related challenges, there was no significant effect in the agreement level, which means that the adopters at different stages and non-adopters expressed similar levels of agreement towards the high service costs, brand compatibility and data privacy and that these three concerns are not fading with the advancement in adoption stages. Therefore, to ensure future PA adopters have an unchallenging user experience, the brand compatibility and data complexity issue should be listed as high priority areas in the agenda to be addressed by a combination of efforts from researchers, technology developers and policy makers.

When crop acres of the farm increase, producers’ perceived cost concerns were significantly reduced. Specifically, when cropland area increases by 1000 acres, producers were 2.2% more likely to disagree with the cost related challenges (Table 5). This cost concern and cropland area relationship could be attributed to the scale effect. Farm size also reduces complexity concerns, in particular ‘not sure how to use PA data effectively’ (Table 7). This is potentially because larger farms, with much higher expenditure on hired labor than smaller farms, could afford to hire specialists to focus on implementing

Table 7 Marginal effects for complexity challenges faced by farmers towards precision agriculture

Variable	Data			Time		
	Disagree	Neutral	Agree	Disagree	Neutral	Agree
Adoption status	0.209***	− 0.177***	− 0.032*	0.215***	− 0.161***	− 0.055***
Cropland area	0.018**	0.003*	− 0.022**	0.009	− 0.001	− 0.008
Ownership	− 0.021	− 0.004	0.025	− 0.014	0.001	0.013
Liability	− 0.020	− 0.004	0.024	− 0.029**	0.002	0.028**
Age	− 0.002*	0.000*	0.003*	− 0.005***	0.000	0.005***
Education	− 0.023	− 0.004	0.027	− 0.007	0.000	0.007
Ag major	0.033	0.006	− 0.039	0.038	− 0.002	− 0.036
Technology	0.075***	0.014***	− 0.089***	0.057***	− 0.004	− 0.053***
Kids	− 0.019*	− 0.004	0.022*	− 0.009	0.001	0.008
Extension	0.006	0.001	− 0.007	− 0.010	0.001	0.009
Machinery dealers	− 0.024*	− 0.004	0.028*	− 0.006	0.000	0.006
HEL	0.004	0.001	− 0.005	0.005	0.000	− 0.005
Saline/sodic	− 0.053***	− 0.010***	0.063***	− 0.017	0.001	0.016
Slope	− 0.012	− 0.002	0.015	− 0.007	0.000	0.007
LCC12	− 0.113*	− 0.022*	0.135*	− 0.027	0.002	0.025
ND	− 0.057	− 0.011	0.067	− 0.037	0.002	0.034
NE	− 0.027	− 0.005	0.033	0.010	− 0.001	− 0.009
MN	0.015	0.003	− 0.018	0.034	− 0.002	− 0.031

Italics indicate statistically significant variables, where ***, **, and * represent $p \leq 0.01$, $p \leq 0.05$ and $p \leq 0.10$, respectively

PA practice (Schimmelpfennig, 2016). Such strategy in specialization efficiently addresses complex concerns for large farms. In contrast, it can be inferred that smaller farms will find PA adoption more challenging due to financial constraints as well as lack of expertise. In this regard, custom service could offer a solution for small farms. Previous literature findings also indicated that small farms were likely to use custom service for precision mapping to target field operations when necessary (Schimmelpfennig, 2016).

Land tenure plays an important role only when it comes to soil suitability to PA usage. Specifically, when a higher proportion of farmland is owned, producers expressed more concerns towards ‘not sure whether soil conditions on my farm will benefit from PA’ (Table 8). This indicates that the owners of the land, when compared to the renters, are more likely to be concerned about the soil suitability. Therefore, information about the soil variability on the specific farm level will likely help owners understand the soil variability of their farm and whether certain PA technologies can be utilized to better manage the soil variability. No significant relationship is observed between farm liability and perceived cost challenge. However, farm liability significantly increased some perceived challenges in the complexity and support category. Specifically, farmers with high liability are more likely to be concerned over ‘PA technology too time-consuming to learn’ and ‘limited information about the best PA technologies for my farm/region’.

When operator age increases by 1 year, they are 0.3% less likely to disagree with the data privacy challenge, while 0.3% more likely to have a neutral opinion (Table 6). It shows that compared to younger farmers, older farmers are more likely to perceive

Table 8 Marginal effects for support challenges faced by farmers towards precision agriculture

Variable	Soil			Information			Research			Map		
	Disagree	Neutral	Agree	Disagree	Neutral	Agree	Disagree	Neutral	Agree	Disagree	Neutral	Agree
Adoption status	0.171***	− 0.140***	− 0.031*	0.129***	− 0.139***	0.010	0.101***	− 0.110***	0.010	0.222***	− 0.154***	− 0.068***
Cropland area	0.000	0.000	0.000	0.004	0.000	− 0.004	0.008	0.002	− 0.011	0.007	− 0.001	− 0.005
Ownership	− 0.103*	0.014*	0.088*	− 0.013	0.000	0.013	− 0.013	− 0.004	0.017	− 0.047	0.009	0.037
Liability	− 0.008	0.001	0.007	− 0.029**	0.001	0.028**	− 0.006	− 0.002	0.008	− 0.021	0.004	0.017
Age	0.000	0.000	0.000	− 0.002*	0.000	0.002*	0.000	0.000	0.001	− 0.002	0.000	0.002
Education	0.015	− 0.002	− 0.013	0.068**	− 0.002	− 0.066**	0.026	0.008	− 0.033	− 0.009	0.002	0.007
Ag Major	0.109***	− 0.015**	− 0.094***	0.038	− 0.001	− 0.037	0.047	0.014	− 0.061	0.087**	− 0.107***	0.020
Technology	0.025	− 0.004	− 0.021	− 0.021	0.000	0.020	− 0.012	− 0.003	0.015	0.038**	− 0.008*	− 0.031**
Kids	− 0.010	0.001	0.009	− 0.014	0.000	0.014	− 0.021***	− 0.006**	0.028***	− 0.015	0.003	0.012
Extension	− 0.006	0.001	0.005	− 0.012	0.000	0.012	− 0.004	− 0.001	0.005	− 0.008	0.002	0.006
Machinery deal- ers	− 0.007	0.001	0.006	0.021	− 0.001	− 0.020	− 0.004	− 0.001	0.005	− 0.002	0.000	0.001
HEL	− 0.022*	0.003*	0.019*	− 0.013	0.000	0.013	− 0.006	− 0.002	0.008	− 0.003	0.001	0.002
Saline/sodic	0.002	0.000	− 0.001	− 0.004	0.000	0.004	− 0.022*	− 0.006*	0.028*	0.002	0.000	− 0.001
Slope	0.021**	− 0.003*	− 0.018**	0.000	0.000	0.000	0.001	0.000	− 0.002	0.008	− 0.002	− 0.006
LCC12	0.118*	− 0.017	− 0.101*	0.072	− 0.002	− 0.071	0.071	0.021	− 0.092	− 0.014	0.003	0.011
ND	− 0.072	0.010	0.062	0.087**	− 0.002	− 0.085**	0.042	0.013	− 0.055	− 0.050	0.010	0.040
NE	− 0.051	0.007	0.044	0.108***	− 0.003	− 0.106**	0.077**	0.023*	− 0.099**	0.025	− 0.005	− 0.020
MN	− 0.088**	0.012*	0.075**	0.044	− 0.001	− 0.043	− 0.018	− 0.005	0.023	0.061	− 0.012	− 0.049

Italics indicate statistically significant variables, where ***, **, and * represent $p \leq 0.01$, $p \leq 0.05$ and $p \leq 0.10$, respectively

Table 9 Marginal effects for infrastructure challenges faced by farmers towards precision agriculture

Variable	Internet		
	Disagree	Neutral	Agree
Adoption status	<i>0.098***</i>	<i>– 0.098***</i>	0.000
Cropland area	0.013	– 0.001	– 0.012
Ownership	– 0.023	0.001	0.022
Liability	– 0.012	0.001	0.012
Age	<i>– 0.003**</i>	0.000	<i>0.003**</i>
Education	0.014	– 0.001	– 0.013
Ag major	<i>0.085**</i>	– 0.005	<i>– 0.080**</i>
Technology	– 0.003	0.000	0.002
Kids	<i>– 0.062***</i>	0.004	<i>0.058***</i>
Extension	– 0.013	<i>– 0.048***</i>	<i>0.061***</i>
Machinery dealers	0.023	– 0.001	– 0.022
HEL	– 0.002	0.000	0.002
Saline/sodic	– 0.013	0.001	0.012
Slope	0.011	– 0.001	– 0.010
LCC12	– 0.058	0.004	0.054
ND	<i>0.083*</i>	– 0.005	<i>– 0.077*</i>
NE	<i>– 0.087*</i>	0.005	<i>0.082*</i>
MN	– 0.009	0.001	0.008

Italics indicate statistically significant variables, where ***, **, and * represent $p \leq 0.01$, $p \leq 0.05$ and $p \leq 0.10$, respectively

data privacy as a concern. In addition, significantly positive relationships exist between age and complexity concerns (Table 7). Older farmers also tend to perceive higher concerns on limited information and internet connectivity (Tables 8 and 9). These indicate that older farmers are more likely to encounter difficulties towards the usage of PA technologies.

Education plays a significant role in reducing concerns about high service costs and limited information. Compared to the producers with high school and technical school degrees, producers with a 4-year college degree or above are 7.8% less likely to agree that service cost associated PA is too high (Table 5). This is probably because higher educated farmers generally have more understanding towards PA benefits and the value of PA service, thereby less likely to regard the service cost as too high. In addition, they tend to be more capable of gathering the needed information. Having an agricultural discipline as their educational major also plays an important role in helping reduce support/infrastructure related challenges of PA usage. Specifically, farmers with an agricultural major are more likely to disagree and less likely to agree with concerns such as ‘whether soil conditions on my farm will benefit from PA’ (Table 8), ‘not confident in prescription maps and agronomic recommendations’ (Table 8), and ‘lack of strong, reliable internet connectivity’ (Table 9).

Additionally, farmers’ personal goals frequently play a role in perceived challenges. Those who ranked ‘keeping pace with new technology’ as one of their most important farm management goals are less concerned with the cost, technology, and complexity related challenges. At the same time, these producers also feel more confident with prescription maps and agronomic recommendations (Tables 5 - 8). In contrast, those

who rated ‘getting kids into farming’ as more important are more concerned with the high equipment costs, service costs, and data privacy (Tables 5, 6). In addition, they demonstrated more concerns towards complexity, limited on-farm research, and internet connectivity (Tables 6, 7, 8). These findings imply that farmers who are motivated to use new technologies tend to overlook the challenges, yet farmers use PA primarily to attract their kids back to farming will perceive more challenges since they might be slow to observe the other benefits generated by the technologies. Such linkages between goals and perceived challenges illustrate that producer perceived challenges are somehow subjective, and there might be other subjective matters not captured here that could affect farmers’ perceived challenges as well.

Surprisingly, farmers who placed more weight towards the role of external information sources were more likely to agree with some of the listed challenges. Specifically, those who rated university extension as a more important source for them when making PA decisions are more likely to perceive PA equipment costs are too high, and more likely to agree that lack of strong internet connectivity posed a challenge (Tables 5 and 9). Meanwhile, those who placed more value upon machinery dealers’ inputs are more likely to agree with the challenges towards brand compatibility and data complexity (Tables 6 and 7). It is likely that farmers who rely more on those information sources to inform their PA usage decisions become more aware of the challenges associated with PA than farmers who use them less as they become more influenced by expert opinions in these matters.

The listed soil characteristics variables also affected farmers’ perceptions towards the following three challenges: brand compatibility, data complexity, and soil suitability (Tables 6, 7, 8). When percentage of land with saline or sodic conditions increases, producers are more likely to perceive challenges towards brand compatibility, data complexity, and lack of on-farm research and demonstration. The percentage of land with LCC I and II plays a double-edged role in terms of perceived challenges. While it increases farmers’ agreement with the brand compatibility and data complexity challenge, it reduces the perceived challenges towards soil suitability (Tables 6, 7, 8). The soil model (Table 8) illustrates that farmers with higher proportions of land suitable for crop cultivation purposes, greater degrees of terrain variation, and less land with HEL conditions, are more likely to be certain that soil conditions on their farms will benefit from PA usage. Therefore, they might represent a target group where PA technology could be further promoted. Furthermore, to facilitate farmers’ decision-making, more research and outreach efforts should be carried out to quantify the benefits of PA on farms with diversified soil and terrain conditions.

While state variables played no role in terms of costs, data privacy and time-consuming nature of the technology, indicating those are universal challenges faced by farmers across all studied regions, they do play a significant role when it comes to infrastructure, support, and brand compatibility. This indicates that the infrastructure and support for farmers across different regions are likely to vary. For example, compared with SD producers, producers from ND and NE perceive less challenges from information limitation, and producers from NE also feel on-farm research and demonstration is less of a challenge (Table 8). Moreover, producers from regions such as MN expressed more concerns towards their soil suitability for PA technologies (Table 8). In contrast, producers from NE are more likely to regard internet connectivity as a challenge (Table 9). These findings illustrate that to address infrastructure and support related concerns, development and outreach efforts could be more tailored towards the unique regional needs to promote efficient PA usage on a regional basis.

Conclusion

Challenges faced by producers towards the PA technologies, if not addressed, could hinder future adoption decisions and inhibit effective utilization of the technology. This paper used farmer survey data from U.S. Midwest to examine the farmer ratings of challenges surrounding their PA adoption and usage decisions. Findings of this paper indicate cost and technology related challenges, namely PA equipment and service costs, compatibility among different brands and data privacy concerns, are among the top and foremost challenges faced by producers.

The results from this study convey that producers with varying experience in PA technologies have different views regarding the main challenges towards PA usage and adoption. Among them, non-adopters and entry adopters demonstrated greatest concerns towards high equipment cost and high service cost, yet least concerns towards the infrastructure and support issues, including the commonly mentioned internet connectivity concerns. Such findings suggest that in comparison to the input towards the local demonstration, information dissemination, and internet connection areas, monetary support such as farm loans and subsidies will more likely address the major concerns faced by these two groups.

Most challenges tend to decrease as adoption intensity increases, and correspondingly, the advanced adopters indicated significantly lower concerns with the cost, complexity, and infrastructure/support issues. Among the list of challenges, lack of compatibility among different brands was ranked as the top concern by the advanced adopters. Additionally, producers at all adoption stages expressed major concerns towards brand compatibility and data privacy issues. Attention and efforts towards addressing such concerns can create a relatively trouble-free experience for PA adopters, especially those who are utilizing information-intensive technologies.

This paper also investigated the potential factors that alter producers' perceived challenges. Through lessening or aggravating farmers' perceived challenges, these factors could affect farmers' PA adoption decisions. While previous literature has been focusing on their roles on PA adoption decisions, their effects on farmers' challenge perceptions have been overlooked. Among these, farm characteristics and farmer demographics affect perceived challenges in significant ways. For example, larger farm size and reduced liability ratio will also help reduce farmer perceived challenges in some categories. Younger and more educated farmers are less likely to perceive challenges regarding PA adoption and usage. Perceived challenges are also subject to personal beliefs and goals as farmers more motivated to use new technologies were less likely to agree with challenges associated with PA usage. Furthermore, soil variability and regional factors matter, as they play significant roles towards perceived challenges in different categories.

Overall, the findings on farmers' topmost concerns towards PA technologies, contingent on their adoption stages, as well as the factors that could lessen or aggravate such perceptions, could be used to identify future directions in research, development, and policymaking. It could also help university extension and PA industry effectively target their outreach and marketing efforts and ultimately enhance the effective usage of PA for all suitable crop production systems. For example, findings from this study indicate producers with college degrees and agricultural majors generally had less concerns with PA technologies, therefore could be a potential target group to promote PA usage. In contrast, older producers and small farm operators face greater challenges due to lack of expertise to address data complexity concerns. Efforts in promoting custom service and training PA specialized labors

will provide such producers with more opportunities in PA usage. Results of this study also illustrate that PA benefits may vary across diversified soil and terrain conditions and therefore, call for more research and outreach efforts to quantify PA benefits in various farm conditions to facilitate farmer decisions. Finally, as farmer concerns over PA technology, support and infrastructure vary across regions, PA promotion efforts should be tailored to identify and address top challenges in different regions.

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Data availability statement The datasets analyzed during the current study are not publicly available due to the confidentiality requirements from Institutional Review Board (IRB) of South Dakota State University.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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