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Farmers' adoption and perceived benefits of diversified crop rotations in the margins of U.S. Corn Belt

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ABSTRACT

Monoculture and simplified two-crop rotation systems compromise the ecosystem services essential to crop production, diminish agricultural productivity, and cause detrimental effects on the environment. In contrast to the simplified two-crop rotation, diversified crop rotation (DCR) refers to rotation systems that contain three or more crops. Despite multiple benefits generated by DCR, its usage has dwindled over the past several decades. This paper examined determinants of farmers' adoption decisions and perceived benefits of DCR in the west margins of the U.S. Corn Belt where crop diversity has declined. We analyzed 708 farmer responses from a farmer survey conducted in the eastern South Dakota in 2018, accounting for county-level climate variables, as well as cropland data, soil and topographic variables in close proximity of the farm. Our findings indicated that farmers were more likely to utilize DCR as an adaptive strategy to cope with water deficit and reduce soil erosion on marginal land. Additionally, livestock integration and organic farming helped necessitate DCR adoption and magnify its benefits. Producer concerns towards lack of equipment and new crop profitability diluted producers' interests in DCR practice and compromised its benefits. Enhanced technical and policy support, along with infrastructure and market development, could help producers fully utilize DCR benefits and expand DCR usage to more regions.

1. Introduction

Agricultural industrialization, which features farm mechanization, intensive use of fertilizers and pesticides, farm specialization, and improved transportation network, has induced a spatial concentration of crop types and loss of crop diversity (Crossley et al., 2020; MacDonald et al., 2013). In the U.S. Midwest, the majority of cropland is currently occupied by either monoculture or simple crop rotations of corn and soybeans (Mulik, 2017). As a dominant crop rotation in the U.S. Midwest, corn-soybean rotation is under expansion during the past several decades, due primarily to increased food and industrial uses, economic and world trade benefits, and tremendous efforts devoted to genetic improvement and infrastructure development (Karlen et al., 2004, 2006; Wang and Chowdhury, 2020).

Nevertheless, monoculture and simplified crop rotation systems compromise the ecosystem services essential to crop production, including soil retention, water provision, nutrient cycling, pollination, and pest control, therefore diminishing agricultural productivity (Burchfield et al., 2019; Kremen and Miles, 2012; Zhang et al., 2007). Topsoil erosion reduces crop yield, and causes an annual profit loss of $2.8 billion on average across the U.S. Corn Belt (Thaler et al., 2021). Furthermore, over-fertilization is common on degraded low-yield fields, and the unutilized N fertilizer lost to the environment alone costs nearly $0.5 billion annually in the U.S. Midwest (Basso et al., 2019). Additionally, monoculture and simplified crop rotation systems have detrimental effects on the environment as runoff of nutrients and agricultural chemicals could contaminate both surface water and groundwater (Montgomery, 2007; Scharf et al., 2005; Robertson et al., 2014).

In contrast to the simplified corn-soybean rotation practice, diversified crop rotation (DCR) refers to rotation systems that contain three or more crops (Bowles et al., 2020; FAO, 2017; Karlen et al., 2006; Wang et al., 2019). Compared to monoculture and simplified crop rotation systems, DCR generates both private benefits to the farmers and public benefits to the society (Archer et al., 2020; Isbell et al., 2017). DCR repairs ecosystem services that are negatively impacted by simplification of agricultural landscape, such as reduced pollination services and lack

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of biological control of pests (Garibaldi et al., 2011; Rusch et al., 2016). DCR also adds organic matter to the soil and reverses soil degradation by substantially increasing the soil microbial biomass C and N pools, which contributes to soil fertility improvement (McDaniel et al., 2014; Tiemann et al., 2015). Additionally, plant diversification significantly reduces soil erosion as noted by Hunt et al. (2019) that three- and four-year crop rotations reduced the soil erosion by up to 60% in the central U.S., which further lowers runoff of environmentally detrimental nutrients and chemicals and leads to improvements in water quality (Beillouin et al., 2020). Greater plant diversity also potentially suppresses weed and pest, therefore providing substitutes for costly and environmentally detrimental chemical inputs such as fertilizers and pesticides (Isbell et al., 2017; Letourneau et al., 2011; MacDonald et al., 2013; Gaudin et al., 2015a). Extended crop rotations also reduce yield variation and improve crop yield, especially during adverse growing seasons, as well as support worldwide agricultural employment opportunities (Bowles et al., 2020; Davis et al., 2012; Gaudin et al., 2015b; Garibaldi and Pérez-Méndez, 2019; Hunt et al., 2019).

Despite multiple benefits generated by DCR, its adoption rate has been declining over the years with a concurrent increase in corn and soybean systems (O'Brien et al., 2020). A mix of economic, political, and biophysical constraints may discourage farmers from adopting DCR. For example, relatively high profitability of corn and soybeans also provides farmers economic incentives to expand corn-soybean acres (Singh et al., 2021). Specialization in one or two crops enables farmers to utilize specialized equipment more intensively and accumulate more crop-specific knowledge (Holmes and Lee, 2012). Farmers may find it difficult to adopt DCR due to barriers such as high initial costs to purchase specialized equipment, insufficient knowledge and technical skills, shortage of local infrastructure, and lack of marketing information for new crop varieties (Mulik, 2017; Prokopy et al., 2019; Singh et al., 2021). Additionally, crop-planting sequences could play a significant role in the successful management of DCR (Anderson, 2011, 2012). Therefore, when transitioning from simplified crop rotation to DCR, it generally takes a relatively long period to experience economic benefits as evidenced by stable net returns and crop yield (Meyer-Aurich et al., 2006). The U.S. Farm Bill, as an all-encompassing legislation, further incentivizes intensive crop production, and therefore, fails to promote crop diversity (Spangler et al., 2020). Lack of available government subsidies and crop insurance for some crops poses extra challenges (Lin, 2011). Furthermore, local climate and soil conditions could constrain successful planting of some new crop varieties to diversify existing cropping systems (Cutforth et al., 2001).

Utilizing experimental field data, a large body of literature has compared simplified vs. diversified cropping systems regarding yield, economic and environmental consequences (Archer et al., 2018; Davis et al., 2012; Gaudin et al., 2015a; Hunt et al., 2017; Jagadamma et al., 2008; Meyer-Aurich et al., 2006; Sindelar et al., 2016; Smith et al., 2017). In contrast, few studies have been carried out to analyze the determinants of farmers' adoption decisions of DCR. As individual farmers make DCR adoption decisions based on a variety of factors such as socioeconomic factors, benefit perceptions, and environmental attitudes, it is important to investigate the conducive and constraining factors for farmers' DCR adoption decisions. Utilizing mail survey responses from a western Corn Belt County in 1998, Cutforth et al. (2001) examined factors that determine farmers' crop diversity decisions. They concluded that DCR was more readily adopted on farms with sloping landscapes and integrated crop-livestock systems. A more recent study by Roesch-McNally et al. (2018) analyzed factors influencing farmers' DCR adoption decisions in U.S. Corn Belt through a farmer survey and in-depth interviews, and they largely confirmed the findings of Cutforth et al. (2001) that farmers with marginal land and/or livestock were more likely to use DCR. Additionally, they found current users were likely to use DCR as an adaptive strategy to climate change.

Due to identified contextual variation in DCR performance, adoption decisions and perceived benefits of DCR could vary on a regional basis (Beillouin et al., 2020). In this paper, we study farmers' adoption decisions in the west margins of Corn Belt–a climate transitional zone of East South Dakota (ESD) that exhibits an east-west declining precipitation gradient (Wang et al., 2021). Only 3% of the harvested acres in the ESD region was under irrigation (National Agricultural Statistics Service NASS, 2017). Crop diversity has greatly decreased in the studied region, with corn and soybean harvest acreage experiencing a considerable increase from 64% in 2002 to 78% in 2017, accompanied by a decline in wheat and hay harvested acres (Aguilar et al., 2015; Lee, 2017; National Agricultural Statistics Service NASS, 2017; Wang and Chowdhury, 2020). Production decisions interrelate with crop infrastructures in the local region. A survey conducted in 2015 among Eastern Dakota farmers found that over the 2006–2015 period, most respondents (60%) perceived improvement ("somewhat better" or "much better") in corn and soybean infrastructures,[1] while only 25% perceived improvement in wheat infrastructure (Wang et al., 2020). Continual increase in simplified crop rotation acres and the negative consequences on environment and ecosystem services underline the importance of sustained DCR adoption in this region (Johnston, 2014).

The determinants of farmers' DCR adoption decisions in our study region have not been well documented. Furthermore, to our knowledge, no research has been done towards farmer perceptions on yield and profitability change after DCR adoption, which is critical to understand the sustained adoption and would be informative to farmers when making future DCR adoption decisions. To fill these knowledge gaps, this paper employs 708 farmer responses from a farm survey conducted in the eastern South Dakota in 2018, coupled with crop acre percentage data from CropScape–Cropland Data Layer (CDL), daily weather data from Parameter-elevation Regressions on Independent Slopes Model (PRISM), and soil data from the gridded Soil Survey Geographic (gSSURGO) and the Soil Survey Geographic (SSURGO) databases. The rest of the paper proceeds with a description of the survey and the datasets used in this study, followed by an explanation of research methodologies. We then present the estimation results of the empirical models and the discussion, with concluding remarks and policy implications provided in the concluding section.

2. Material and methods

2.1. Survey description

This study used data collected from a farmer survey conducted in eastern South Dakota in the spring of 2018. The dominant rotation in the region is a two-year corn and soybean rotation, which occupied 78% of the harvested acreage as of 2017 (National Agricultural Statistics Service NASS, 2017). For 22 counties in eastern South Dakota predominated by conventional tillage, Natural Resources Conservation Service (NRCS) reported an average farm acre ratio of 1:28 between small grains and row crops (comprised almost exclusively of corn and soybeans) in 2013 (NRCS, 2014). The survey asked farmers about their views and usage of farming practices to help understand farming decisions and inform policies. It contains 16 pages (including cover page), and requires approximately 20 min to complete. There are six sections in the survey, namely 1) farm and farmer characteristics; 2) farming decisions; 3) farm management practices; 4) benefits and challenges to the adoption of soil conservation practices; 5) cost and benefit perceptions; and 6) community and environment.

We sent survey questionnaires to a representative sample of 3000 farm operators selected from the participants in Farm Service Agency (FSA) programs using proportionate stratified-random sampling. We contacted the selected farmers in four rounds from January to March in

[1] Infrastructure in the survey is defined as "transportation, market outlets, equipment and agronomic services to support production of different agricultural products".

2018. First, an advanced letter was sent to each participant with the information and purpose of the survey and a link to answer the questionnaire online. For producers who did not respond to the online survey questionnaire, we then mailed the paper questionnaires and stamped return envelopes. A reminder postcard was mailed two weeks after the mailing of the first questionnaire. After another two weeks, we sent the second mailing of the questionnaire and a stamped return envelope to the producers who did not respond to the first mailing of questionnaire. In total, we received 708 responses, and the response rate was 30% after we excluded the operations that reported no longer farming from the total sample.

As natural land characteristics such as precipitation, soil type, and land slope could affect farmers' crop choices (Holmes and Lee, 2012), we matched the farmer address information provided by FSA with the county-level weather data from PRISM and soil information from gSSURGO and SSURGO databases supplied by NRCS. As survey results indicated the majority (58%) of South Dakota ranchers live within 3 miles of their largest tract of grazing land (Wang et al., 2020), we geocoded farmers' residential addresses using ArcGIS software, and created 3- and 5-mile buffers for each South Dakota respondent's address with average soil variable information calculated for each buffer. Due to the likely geographic autocorrelation and similar soils in the 40-acre quarter sections (Holmes and Lee, 2012), our 3-mile buffer soil properties should be highly correlated with and reflect the soil properties of the farmers' fields, which thereby allowed us to control for spatial heterogeneity among the surveyed farmers in eastern South Dakota. To capture the effect of crop rotation complexity in the local region, we also included crop acre percentage within a 5-mile buffer of each respondent's address. Crop acre percentages were obtained from CDL and averaged across three consecutive years prior to our survey, i.e., 2015, 2016 and 2017 (NASS, 2020).

2.2. Variable description

Fig. 1 demonstrates the average adoption rate of DCR for each surveyed county, with the number of respondents included in the parentheses. The average county-level adoption rate shows a visible increasing pattern when moving from east to west, which corresponds to the east-west declining precipitation gradient of the study region. This study categorized farmers based on their DCR adoption status, and further classified adopters of DCR based on their years of usage.

For the current users, we asked about the proportion of their operated land under DCR practice. Additionally, we asked DCR adopters to rate the changes in cash crop[2] yields and profits after adoption, on a scale of 1–5 denoting 'reduced by >15%', 'reduced by 5–15%', 'very little change (within 5%)', 'increased by 5–15%', and 'increased by >15%', respectively. We grouped variables that potentially affect producers' DCR adoption decisions and adopters' benefit perceptions into three categories: farmer characteristics, farm characteristics and management, and farmer attitude and perception. Within the farmer characteristics category, early adopters refer to adopters who had used DCR for more than 10 years. We included producers' operation years as a potential explanatory variable. Farmers with a longer operation period generally accumulate more experience and have more resources to implement conservation practices (Prokopy et al., 2019). However, farmers with more experience are generally older and may not be willing to make changes in farm practices given their shorter planning spans in the future. Similarly, education could positively or negatively correlate with the adoption of conservation practices (Knowler and Bradshaw, 2007; Prokopy et al., 2019). While more educated farmers are likely to have greater awareness of the on- and off-site benefits of conservation practices, they may be unwilling to implement any new practices due to high opportunity costs. Therefore, the role of education on DCR adoption is ambiguous.

Under the farm characteristics and management category, the effect of off-farm income on DCR adoption is also ambiguous (Knowler and Bradshaw, 2007; Prokopy et al., 2019). On the one hand, farmers with more off-farm income may not have sufficient time to learn about the new practice. On the other hand, farmers with more off-farm income may be more financially stabilized, and therefore they could more readily afford the new equipment required by DCR practice. Farmers were asked to choose their off-farm income status on a scale of 1–5, with 1 being less than 20% and 5 being more than 80%. Annual gross sales variable was included in the model to capture the economies of scale effect on a scale of 1 (less than $50,000) to 6 (more than $1 million). Due to the required new equipment for DCR adoption, we expected larger farms to be more willing to adopt DCR as they can spread the upfront equipment and learning costs to more acres of their land.

We also included livestock as an explanatory variable as DCR would be more feasible in regions with viable livestock production (Cutforth et al., 2001; Roesch-McNally et al., 2018). Organic farm is also considered as a potential explanatory variable for adoption decisions and benefit ratings. Extended crop rotation is often associated with organic farming systems because organic farms are absent of chemicals, and thereby they are more reliant on biological methods to control pests (Garratt et al., 2011; Muneret et al., 2018).

For the attitude and perception category, we included farmers' attitudes towards their business development and agricultural technology, as well as their perceptions of certain benefits and barriers associated with DCR adoption. Producers were asked about their agreement level (from 1 = 'Strongly disagree' to 4 = 'Strongly agree') on the statement 'Technical advances in seeds, fertilizers, and pesticides can offset the adverse effect of soil erosion on productivity'. Suppose producers perceive technology advancement as a likely solution to address the negative effect of soil degradation, then it is unlikely for them to adopt conservation practices such as DCR.

Lack of planting and harvesting equipment could pose a potential challenge for producers, especially when profit margins are slim. While production costs for other crops are often considerably lower than those for corn and soybeans, the initial investment in special equipment could impede the adoption decisions of financially constrained farmers (Mulik, 2017; Singh et al., 2021). Additionally, relatively low profitability of potential 3rd and 4th crops could be another barrier to farmers' adoption decisions from an economic perspective. Additionally, more knowledge about the benefits of conservation practices could positively affect producers' adoption decisions (Carlisle, 2016). Producers were asked about the two main benefits of DCR–breaking pest and disease cycle and reducing fertilizer input.

Farmers' own decisions and neighborhood farming decisions are mutually influential (Tsusaka et al., 2015). Furthermore, increased crop rotation complexity in the local region will likely promote the development of infrastructure for the extended rotation crops (e.g., agronomic services, cropping equipment, and market outlets), therefore potentially affecting farmers' crop diversification decisions. To investigate the effect of local crop diversity on farmers' rotation decisions, we obtained the percentage of planted acres under spring/winter wheat, oat, and alfalfa from CDL. The summed percentage of these commonly used extended rotation crops was used as a crop diversity indicator. Additionally, the biophysical constraints such as climate conditions could significantly contribute to crop development and yield, therefore affecting farmers' adoption decisions of conservation practices (Knowler and Bradshaw, 2007; Prokopy et al., 2019). We used the 30-year (1987–2017) average temperature and precipitation between May and September to capture the effects of growing-season climate variables on farmers' adoption decisions. Higher temperature could aggravate soil water shortage and DCR has been recommended as an adaptive strategy to improve the resilience of farming systems challenged by extreme temperature (Di Falco and Chavas, 2008; Hatfield et al., 2011; Lin, 2011; Lakhran et al., 2017). Based on the interview findings of

[2] Cash crops refer to crops that farm grows for sales or profit purpose.

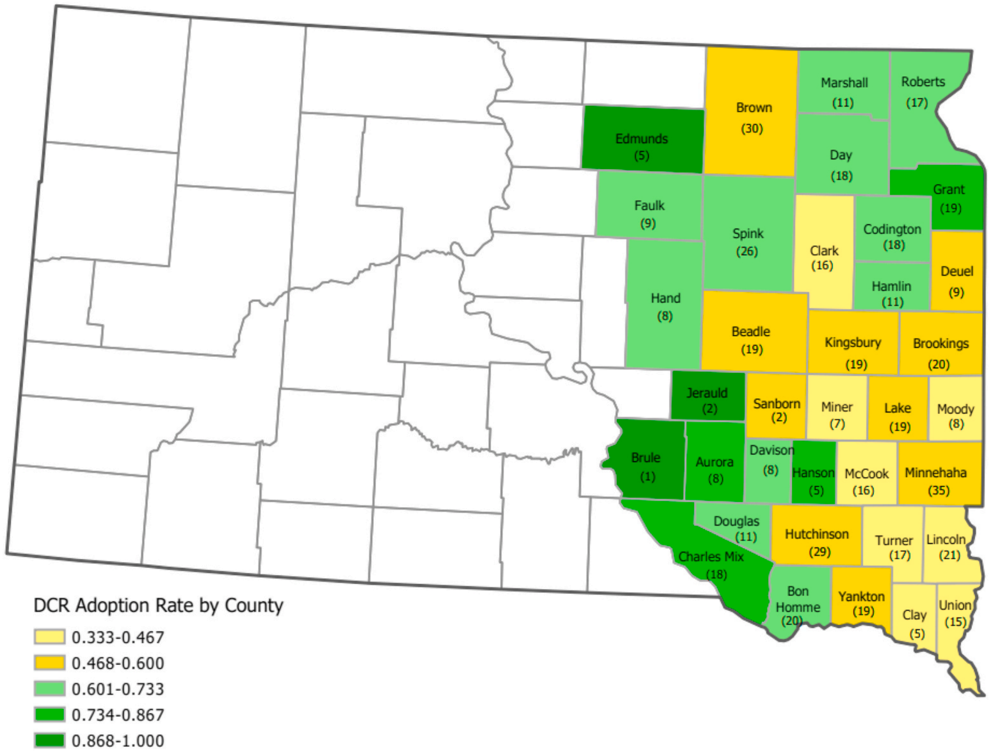

Fig. 1. Diversified crop rotation (DCR) adoption status at the county level in East South Dakota, based on the responses from 2018 South Dakota farmer survey. Note: Numbers in the parentheses denote the number of respondents in each county.

Roesch-McNally et al. (2018), a number of farmers indicated modification of their crop rotation as a response to weather extremes, including planting wheat as an alternative crop during dry years. Therefore, we expected DCR to be more commonly practiced in the areas with lower precipitation.

Soil characteristics could also affect crop yield, farm income, and soil erodibility (Yun and Gramig, 2019; Socolar et al., 2021). To capture factors that potentially affect farmers' crop rotation choices, we included 1) soil characteristics (available water capacity, land capability class, bulk density, soil organic matter) that affect crop yield and farm profit; and 2) soil characteristics (slope) that influence soil erosion potential[3] (Wu and Babcock, 1998). Among these, available water capacity (AWC) measures the amount of water that a soil can store for growing plant, which is not only affected by precipitation, but also by soil texture. While soils containing a higher proportion of sand drain faster, soils containing a higher proportion of silt or clay drain more slowly and positively affect AWC (Jaja, 2016). We used land capability class (LCC) as an indicator for crop production constraints. In contrast to LCC III and above, LCC I and II soils have few limitations in soil topography and climate, therefore they are most suitable for the production of cultivated crops. Soil organic matter (SOM), formed by plant and animal material in process of decomposing, is a primary indicator for soil fertility. Additionally, bulk density was included as an indicator of soil compaction that could substantially reduce agricultural productivity and farm income. Soils with low bulk density are generally more suitable for agriculture, since the high pore space has a greater potential to store water and allow roots to grow more readily (Shah et al., 2017). Finally, land slope measures the degree of variability in the terrain and is an indicator of highly erodible land (HEL), and therefore the fields with a steeper slope are more susceptible to erosion. In alignment with Cutforth et al. (2001), we expected farmers to more likely adopt DCR practice on steeper sloped land.

2.3. Empirical model

Two models are estimated in this paper to investigate 1) factors affecting farmers' DCR adoption decisions; 2) factors that influence DCR adopters' perceived changes in crop yield and profitability. On DCR adoption decisions, we assume farmer i's decision is contingent on the comparative value of the utility under non-adoption or simplified crop rotation practice (U_i^S) and the utility under adoption or DCR practice (U_i^D). Farmer i will adopt DCR ($DCR_i = 1$) if $\Delta U_i = U_i^D - U_i^S > 0$, and not adopt ($DCR_i = 0$) if $\Delta U \leq 0$. From our survey sample, we can observe farmers' DCR adoption decisions, where we assign $DCR = 1$ for all current adopters regardless of their duration of usage, and $DCR = 0$ for farmers who had never used DCR. We excluded those farmers who had discontinued DCR in our regression analysis. A probit model is commonly used to explain factors affecting the likelihood of adoption, which is specified as:

$$\Delta U_i = X_i^{'}\beta + \varepsilon_i$$
$$DCR_i = 1 \; if \; \Delta U_i > 0, \; DCR_i = 0 \; if \; \Delta U_i \leq 0 \quad (1)$$

Note that X_i denotes the vector of explanatory variables, which include variables that fall under four categories: 1) farmer characteristics; 2) farm characteristics and management; 3) attitude and perception; and 4) crop diversity, climate and soil characteristics; β stands for the vector of coefficients; and ε_i denotes the error term that follows a standard normal distribution function (Greene, 2018).

As pointed out by Cary and Wilkinson (1997), sustained conservation practice adoption is contingent on adopters' perceived profitability of the new practice. Therefore, we also asked current DCR adopters to rate

[3] Under this category we also tried to include soil texture determinants, clay and sand percentage, to capture soil erodibility, as low clay and/or high sand contents are less cohesive and are subject to a greater risk of soil erosion (Zhao et al., 2011). However, both variables had high variance inflation factor (VIF) values (7.97 for sand; 3.56 for clay), therefore they were eliminated from the final model due to multicollinearity concerns.

their cash crop yield change and their profit change after DCR adoption, which were reported in five intervals: (i) reduced by more than 15% (<−15%); (ii) reduced by 5%–15% (−15% to −5%); (iii) very little change (within 5%, or −5%–5%); (iv) increased by 5%–15% (5%–15%); and (v) increased by more than 15% (>15%). To control for selection bias issue potentially arising due to unobservable variables that are correlated with both producers' adoption timing (i.e., early adopter or not) and their rated yield and profit outcomes, we estimated a two-step Heckman model. In the first step, we estimated the early adoption model, using a probit regression to determine the factors influencing producers' early adoption decisions. In the second step, we estimated the outcome models to estimate the factors that affect adopters' ratings on yield and profit changes. The two-step Heckman model is specified as:

$$E_i^* = X_{1,i}^{'}\beta_E + \varepsilon_{E_i} \tag{2}$$

$$Y_{k,i}^* = \gamma_k 1[E_i = 1] + X_{2,i}^{'}\beta_k + u_{k,i} \tag{3}$$

Equation (2) stands for the early adoption model, where E_i^* is a latent variable that determines whether farmer i is an early adopter of DCR, $X_{1,i}^{'}$ denotes the vector of explanatory variables that affect the timing of adoption, and β_E refers to the vector of coefficients. Equation (3) describes the outcome models, where k = 1,2 indexes adopters' rated yield and profit changes after DCR adoption and $Y_{k,i}^*$ (k = 1,2) denotes latent variables for the rated yield and profit changes. The indicator function $1[E_i = 1]$ is equal to 1 if $E_i = 1$ and 0 otherwise; γ_k is the coefficient for early adoption status; β_k is the coefficient vector for other variables that affect adopters' rated changes in cash crop yield and profit.

We estimated equation (3) using both bivariate probit models and bivariate interval regression models, and the difference between the two is that the interval regression assumes known cut points, rather than the unknown cut points in the probit regression. Specifically, for the bivariate probit models, we assume $Y_{k,i}$ (k = 1, 2) takes 5 different values, with 1 = reduced by more than 15%; 2 = reduced by 5%–15%; 3 = very little change; 4 = increased by 5%–15%; and 5 = increased by more than 15% (Table 3). As few adopters selected the categories 1, 2, and 5, we combined the first three categories as 1 = 'no improvement', and the last two categories were combined into 2 = 'improvement' category. For the interval regression models, we used the following values to approximate the five categories $Y_{k,i} \leq -15\%$, $-15\% \leq Y_{k,i} \leq -5\%$, $-5\% \leq Y_{k,i} \leq 5\%$, $5\% \leq Y_{k,i} \leq 15\%$, and $Y_{k,i} \geq 15\%$.

As the yield and profit outcomes are likely to correlate with each other, and both outcomes could be affected by the timing of adoption, we first estimated the early-adoption decision model and two outcome models simultaneously, assuming the error terms, ε_{E_i} and $u_{k,i}$, follow a bivariate normal distribution with zero mean and a correlation of ρ_k.

$$\left(\begin{matrix}\varepsilon_{E_i} \\ u_{k,i}\end{matrix}\middle| x_1, x_2\right) \overset{i.i.d.}{\sim} N\left[\begin{pmatrix}0\\0\end{pmatrix}, \begin{pmatrix}1 & \rho_k\sigma_k \\ \rho_k\sigma_k & \sigma_k^2\end{pmatrix}\right]$$

Note that the correlation parameter ρ_k measures the tetrachoric correlation between E_i^* and $Y_{k,i}^*$ (k = 1,2). While the variance of ε_{E_i} is normalized to unity, the variance of $u_{k,i}$ is σ_k^2, which is normalized to unity only in the probit regression. Using Stata software, we estimated the conditional mixed process model and the marginal treatment effect using the "cmp" package (Roodman, 2011) and the "mtefe" package (Anderson, 2018). Both methods showed that the correlation between the error terms of the early-adoption model and the outcome models were not significant at 10% level. Hence, we concluded that the early adoption decisions were not correlated with the rated yield and profit changes, and that the outcome models could be estimated independently from the early adoption model.

Compared with the probit regression, interval regression models are more efficient due to its customized estimated residual variance (Yang et al., 2012). Therefore, for the outcome models we only focused on explaining the results from the bivariate interval regression. The bivariate probit regression results are provided in the appendix A for robustness check purpose. The same set of explanatory variables are included in the bivariate interval regression and the bivariate probit regression. Compared to the length of farming experience, duration of DCR adoption will more likely affect producers' perceptions towards DCR outcomes. Therefore, the outcome models dropped the 'experience' variable from the DCR adoption model but included the 'early adopter' variable. Additionally, the outcome models dropped two additional variables, 'tech offset' and 'equipment availability', as both are likely to affect adoption decisions but once DCR were adopted, these issues are irrelevant and do not pertain to the outcome perceptions.

3. Results and discussion

3.1. Variable statistics

Of the 680 respondents who answered the DCR adoption question, 240 (35.3%) had never used DCR, and 53 (7.8%) indicated that they had used DCR in the past but discontinued the practice (Table 1). Among the remaining 387 (56.9%) producers who were current users of DCR, the majority (211) indicated usage of more than 10 years, which accounted for 54.5% of the adopters and implied less than half new adoption during the recent decade. The DCR adoption rate of 56.9%, based on our survey data, is relatively high compared with the 2017 Census of Agriculture data, according to which only approximately 30% of harvested acres were planted with crops other than corn and soybeans. Additionally, most respondents in our survey identified their typical crop rotation as either continuous (18.7%) or 2-year crop rotation (57.7%), while only 17.4% of producers identified their typical rotation patterns as 3-year

Table 1
Diversified crop rotation (DCR) usage status and rated yield and profit changes, based on 2018 South Dakota farmer survey.

DCR usage	Number of producers	Percent of producers	Percent of land in use	Rated yield change[b]	Rated profit change[b]
Never used	240	35.3%	–	–	–
Less than 3 years	76	11.2%	16.3% C	3.094 B	3.188 AB
3–5 years	48	7.1%	42.0% B	3.419 AB	3.209 AB
6–10 years	52	7.7%	45.5% B	3.298 AB	3.277 AB
More than 10 years[a]	211	31.0%	67.5% A	3.508 A	3.542 A
Discontinued	53	7.8%	–	3.170 AB	3.021 B
Total	680	100%	47.8%	3.364	3.352

Note: Different capital letters in a column indicate statistically significance at the 5% level based on Tukey's Studentized Range test.
[a] Producers who adopted DCR for more than 10 years are also referred to as early adopters.

[b] Rated yield and profit changes (adopters only): 1 = Reduced by >15%; 2 = Reduced by 5%–15%; 3 = Very little change (within 5%); 4 = Increased by 5–15%; 5 = Increased by >15%.

rotations, and 6.2% used 4-year or more diversified crop rotations. The seeming discrepancy between survey-based DCR adoption rate and census-based harvested acres as well as that between DCR adoption rate and typical crop rotation pattern, could be potentially explained by the magnitude and frequency of DCR usage on the farm. Based on our survey findings, some DCR adopters may only use DCR on a small percentage of their farm (Table 1), and some of them may only use DCR practice in some years with unusual weather conditions (Roesch-McNally et al., 2018).

The average DCR land use share in 2017, as reported by DCR adopters, was 47.8%, which started from 16.3% for users under 3 years and gradually increased to 67.5% for users of more than 10 years, demonstrating an increase in DCR land share as the usage time increases (Table 1). While adopters of more than 10 years provided significantly higher ratings on the yield change when compared to those of less than 3 years, no difference was found for the rated profit change among the adopters of different usage durations. We later refer to the adopters of more than 10 years as 'early adopters' when investigating the factors that affect adopters' ratings on yield and profit changes. Among 387 current DCR users, 211 (54.5%) were early adopters. The overall distributions of producer rated changes on the cash crop yield and profitability were summarized in Table 2. Over 80% of the responses fell under the 'very little change (within 5%)' and 'increased by 5–15%' categories, which indicates DCR generates slight yet positive changes in yield and profit for most adopters.

To better understand the types of crop rotation systems in our study region, we asked producers about their previous-year (2017) acres planted with major crops in the region, including corn, soybeans, small grains, and clover/alfalfa. Most respondents indicated that they had acres under corn (86.2%) and soybeans (88.0%), 50.2% operated alfalfa or clover acres, while only less than 30% had acres under small grains, including oats, spring wheat and winter wheat (Table 3). Among the rotation types, only 13.4% planted one crop continuously, while 37.8% of producers used a 2-year rotation system. The majority of producers (86%) under 2-year rotation system used the corn-soybean rotation. As of 2017, 48.7% of the respondents have their crop acres occupied by three or four crop species. Among the producers who used 3-year rotation, over 70% (21.8% out of 30.1%) were under the corn-soybean-alfalfa/clover rotation, and 23% were under corn-soybean-small grain rotations.

Table 4 lists the survey-based explanatory variables that potentially affect producers' DCR adoption decisions and adopters' ratings of DCR benefits. In our study region, farmers on average had nearly 27 years of farming experience and received some college education, as indicated by a mean value of 3.14 on education. Of the farm characteristics and management category, the average off-farm income was 2.21, indicating producers on average had about 20–40% of the household income from off-farm income sources. The average gross sales took the value of 3.35, which lies between 3 = '$100,000 - $249,000' and 4 = '$250,000–499,999'. Among the respondents, 58% indicated integration of livestock into their cropping systems. While only 7% of the farmers that responded to our survey claimed to have organic farms, organic farming has a promising future due to the increasing demand and price premiums for organic products globally (Reganold and Wachter, 2016).

Regarding farmer attitude variables, average producer rating was 2.67 for 'technology offset' (Table 4), indicating that most producers were leaning towards agreement with such statement and trusted in technical advances such as improved seed varieties, fertilizers, and pesticides as an effective way to deal with the adverse effects of soil erosion. Towards the potential challenges, the average ratings for equipment availability and other crop profitability barriers were 2.46 and 2.86 respectively, indicating that the profitability issue could pose a greater challenge than the equipment availability. Similarly, the average values of 3.19 and 2.77 for the two benefits suggested that while most producers agreed on DCR's benefits in controlling pest and disease, fewer farmers had realized DCR's benefit in cutting fertilizer requirement.

In our studied region, the crop diversity indicator, as the summed percentage of planted acres in spring wheat, winter wheat, oat and alfalfa, ranged from 0.44% to 29.04% with a mean of 7.83% (Table 5). The 30-year county average growing-season precipitation ranged from 337.29 to 491.72 mm, and the average temperature ranged between 17.91 and 20.25 Celsius degrees. This suggests a greater variation for precipitation in comparison to temperature in the studied region. AWC in our studied region ranged from 10.17 to 19.90% with an average value of 16.40%. On average, soils with LCC I and II take 9.19% and 52.72% respectively, indicating that most of the soils are of LCC II type and have few limitations for crop cultivation. SOM ranged from 1.02 to 2.10% with an average value of 1.42%. As bulk density of less than 1.5 g/cm3 is considered desirable for air and water movement through the soil (Hunt and Gilkes, 1992), the mean bulk density of 1.37 g/cm3 (ranging from 1.10 to 1.46) suggests that bulk density in the study area is suitable for root growth. Land slope in our study varied between 1.00 and 9.85% with a mean value of 2.96%. The correlation matrix and associated significance levels of local crop diversity, weather, and soil data are provided in the appendix Table A2.[4]

3.2. Diversified crop rotation (DCR) adoption and determinants

To understand the factors that affected producers' DCR decisions, we present the probit model estimation results in Table 6. The dependent variable is the DCR adoption decisions, which is denoted as 0 for producers who had never used DCR, and 1 for current users of DCR regardless of the adoption duration. As indicated in Table 1, 53 producers (7.8%) in our survey sample discontinued DCR, which we excluded from our analysis. Table 6 reports the estimated coefficient (β) and standard error for each explanatory variable. As the estimated coefficient for the probit models cannot be interpreted directly, we also reported the estimated marginal effect, which was calculated for each observation in the sample and averaged across all the observations.

To explore whether local crop diversity, weather and soil variables are highly correlated, we presented the correlation matrix of those variables in Table A2. We also tested multicollinearity issue using variance inflation factor (VIF). The VIF values for all variables were below 3.30 with the mean VIF of 1.72, which suggests no evidence of multicollinearity in the model. The pseudo-R^2 value for the probit regression was 0.25, which is acceptable for conservation practice

Table 2
DCR adopters' rated cash crop yield and profit changes after adoption, based on 2018 South Dakota farmer survey.

Categories	Cash Crop Yield Change		Profit Change	
	Frequency	Percent	Frequency	Percent
Reduced by more than 15%	6	1.99	4	1.32
Reduced by 5%–15%	24	7.97	28	9.21
Very little change (within 5%)	142	47.18	142	46.71
Increased by 5%–15%	107	35.55	106	34.87
Increased by more than 15%	22	7.31	24	7.89
Total	301	100	304	100

[4] For the soil variables included in the model, we were able to gather their spatial variation within 3- and 5-mile buffers of the farmers' home address. We found that on top of the mean values, some soil spatial variation variables also affect local crop diversity, or the summed acre percentage of commonly adopted 3rd and 4th crops within the 5-mile buffer. However, no soil spatial variation variables were found to have a significant effect on farmers' DCR adoption decisions, probably since the spatial variation in farmers' local region do not always represents their intra-operational soil variability. Future studies may use farmers' field-level information to shed more insights on this issue.

Table 3
Joint and marginal probabilities of crop rotation types in East South Dakota.

Crop rotation types	Rotation System Percentage	Crop Percentage			
		Corn	Soybeans	Small grains	Alfalfa/clover
Continuous	**13.4%**				
Corn only	3.0%	3.0%	–	–	–
Soybeans only	5.6%	–	5.6%	–	–
Small grains only	0.2%	–	–	0.2%	–
Alfalfa/clover only	4.7%	–	–	–	4.7%
2-year rotation	**37.8%**				
Corn + Soybeans	32.4%	32.4%	32.4%	–	–
Corn + Small grains	0.5%	0.5%	–	0.5%	–
Corn + Clover/alfalfa	1.7%	1.7%	–	–	1.7%
Soybeans + Small grains	1.2%	–	1.2%	1.2%	–
Soybeans + Alfalfa/clover	1.2%	–	1.2%	–	1.2%
Small grains + Alfalfa/clover	0.7%	–	–	0.7%	0.7%
3-year rotation	**30.1%**				
Corn + Soybeans + Small grains	7.0%	7.0%	7.0%	7.0%	–
Corn + Soybeans + Alfalfa/clover	21.8%	21.8%	21.8%	–	21.8%
Corn + Small grains + Alfalfa/clover	1.2%	1.2%	–	1.2%	1.2%
Soybeans + Small grains + Alfalfa/clover	0.2%	–	0.2%	0.2%	0.2%
4-year rotation	**18.6%**				
All four	18.6%	18.6%	18.6%	18.6%	18.6%
Total	100.0%	86.2%	88.0%	29.6%	50.2%

Table 4
Description and statistics of survey-based explanatory variables.

Category	Variable	Description	N	Mean	Std Dev	Min	Max
Farmer Characteristics	Early adopter	Adopters that used DCR for more than 10 years (1 = Yes; 0 = No)	387	0.55	0.50	0	1
	Experience	Number of years as a primary decision maker for the operation	629	26.61	15.90	0	70
	Education	Highest education level of the respondent (1 = Less than high school; 2 = High school; 3 = Some college, 4 = College degree; 5 = Post-graduate degree)	646	3.14	0.94	1	5
Farm Characteristics and Management	Off-farm	Percentage of household income from off-farm employment (1 = '<20%', 2 = '20–40%', 3 = '41–60%, 4 = '61–80%, 5 = '>80%')	628	2.21	1.49	1	5
	Sales	Annual gross sales (1 = '< $50,000', 2 = '$50,000–99,999', 3 = '$100,000–249,999', 4 = '$250,000–499,999', 5 = '$500,000–999,999', 6 = '> $1 million')	617	3.35	1.56	1	6
	Livestock	Integrated livestock in cropland (1 = Yes, 0 = No)	641	0.58	0.50	0	1
	Organic	1 = 'organic', 0 = 'non-organic' farming operation	631	0.07	0.26	0	1
Attitude and Perception	Tech offset	Technical advances in seeds, fertilizers, and pesticides can offset the adverse effect of soil erosion on productivity (1 = Strongly disagree; 2 = Disagree; 3 = Agree; 4 = Strongly agree)	632	2.67	0.83	1	4
	Equipment availability	Lack access to the specialized planting equipment (1 = Not important; 2 = Slightly important; 3 = Moderately important; 4 = Very important)	620	2.46	1.05	1	4
	New crop profitability	Lack of a profitable 3rd/4th crop (1 = Not important; 2 = Slightly important; 3 = Moderately important; 4 = Very important)	621	2.86	1.01	1	4
	Pest cycle	DCR breaks pest and disease cycle (1 = Strongly disagree; 2 = Disagree; 3 = Agree; 4 = Strongly agree)	634	3.19	0.61	1	4
	Fertilizer cut	DCR reduces fertilizer requirement (1 = Strongly disagree, 2 = Disagree, 3 = Agree, 4 = Strongly agree)	631	2.77	0.67	1	4

adoption studies (Fan et al., 2017; Lee and McCann, 2019). Crop rotation decision is considered as a dynamic process, intermingled with a number of other decisions that vary from farm to farm (Dury et al., 2013). The relatively low R^2 is an indication that some omitted variables in our model, such as business goals, knowledge constraints, market outlets, and risk attitudes, could also affect farmers' DCR adoption decisions.

Table 6 shows that producers' education significantly affects their DCR adoption decisions. This finding indicated that farmers with a higher level of education were more likely to be specialized in production of fewer crops. Similarly, Wang et al. (2019) also found producers with a higher-level education were more likely to be specialized in either crop or livestock production. Farm size also matters in DCR adoption. Consistent with the finding of Wang et al. (2019), we found larger scale farms, as indicated by the higher gross sales, were more likely to diversify crop production. In this regard, Holmes and Lee (2012) also pointed out that larger farms could achieve economies of scale and spread the cost to more acres. Similar to the finding of Roesch-McNally et al. (2018) that producers with livestock were more likely to use extended crop rotations, we also found producers who integrated livestock in their cropping system were 23.8% more likely to adopt DCR practice. This implies that integrating livestock with cropping systems not only provides an opportunity to prevent grassland to cropland conversion (Smart et al., 2020), but also enhances the prospect of diversifying crop rotations in the margins of Corn Belt.

Other than farmer and farm characteristics, we can see attitudes and perceptions play a significant role as well. Among them, farmers who relied more on technology as a solution for soil degradation issues were less likely to adopt DCR. Lin (2011) pointed out that the focus of technology strategies to build the resilience of agricultural systems could be a hindrance to promotion of more diversified systems. While technology advancement in agriculture such as genetic improvement in crop varieties will help increase yield and reduce environmental consequences, conservation agriculture principles such as crop diversification

Table 5
Description and statistics of CDL crop layer, weather and soil variables matched with survey data (N = 614).

Variable	Description	Mean	Std Dev	Min	Max
Crop diversity	Percentage of planted acreage in spring/winter wheat, oat and alfalfa within a 5-mile buffer of each producer's address	7.83	4.99	0.44	29.04
Temperature	30-year average temperature in Celsius (May–September)	18.91	0.74	17.91	20.25
Precipitation	30-year average precipitation in millimeter (May–September)	417.36	37.77	337.29	491.72
AWC	Available water capacity (%)	16.40	1.67	10.17	19.90
LCC I	Soils with land capacity class (LCC) equal to I (%)	9.19	13.23	0.00	62.96
LCC II	Soils with land capacity class (LCC) equal to II (%)	52.72	19.52	1.72	90.86
SOM	Soil organic matter (SOM) consisting of plant and animal material in process of decomposing (%)	1.42	0.21	1.02	2.10
Bulk density	Weight of dry soil per unit of volume (g/cm3)	1.37	0.06	1.10	1.46
Slope	Slope of the field (degree)	2.96	1.49	1.00	9.85

emphasize regenerating degraded land and promoting soil health and resilient cropping systems with less reliance on fertilizer and pesticide input (Hunt et al., 2017; St. Luce et al., 2020). A better understanding of the conservation principles and their indispensable roles towards long-term sustainable agriculture will help farmers make educated farming decisions that are beneficial to the agroecosystems and the environment.

Producers who indicated a concern for lack of specialized planting equipment were less likely to adopt DCR practice. Additional crops to the farm may require substantial investment cost for new equipment, which could pose a barrier to some farmers (Mulik, 2017). This is especially the case during the years of lower crop prices and reduced farm income margins, and farmers would prefer repairing old machines than purchasing new ones (Shepel, 2020). On the benefit side, producers who perceived DCR effective in controlling pest and diseases by breaking their cycles were more likely to adopt DCR. While farmers mostly relied on externally applied pesticides to control pest, the expansion of pesticide resistant weeds and growing pesticide expenditure may necessitate the need for alternative pest control methods (Livingston et al., 2015; Wang and Adhikari, 2020). Therefore, producers who perceived more about DCR's benefit in pest control would have greater incentives to adopt the practice.

Table 6
Probit model estimation results for diversified crop rotation (DCR) adoption.

Category	Variables	Parameter Estimate		Marginal Effect	
		Coeffi.	Std. Err.	dy/dx	Std. Err.
Farmer Characteristics	Experience	0.002	0.005	0.001	0.001
	Education	−0.264***	0.083	−0.073***	0.022
Farm Characteristics and Management	Off-farm	−0.017	0.052	−0.005	0.014
	Sales	0.139***	0.051	0.038***	0.014
	Livestock	0.864***	0.149	0.238***	0.036
	Organic	0.011	0.302	0.003	0.083
Attitude and Perception	Tech offset	−0.174*	0.091	−0.048*	0.025
	Equipment availability	−0.309***	0.081	−0.085***	0.021
	New crop profitability	0.035	0.084	0.010	0.023
	Pest cycle	0.528***	0.141	0.145***	0.037
	Fertilizer cut	−0.036	0.126	−0.010	0.035
Crop Diversity, Climate and Soil	Crop diversity	0.008	0.017	0.002	0.005
	Temperature	0.253	0.160	0.070	0.044
	Precipitation	−0.010***	0.003	−0.003***	0.001
	AWC	−0.192**	0.080	−0.053**	0.022
	LCC I	0.011	0.010	0.003	0.003
	LCC II	0.005	0.007	0.001	0.002
	SOM	0.654	0.554	0.180	0.152
	Bulk density	2.695*	1.441	0.741*	0.392
	Slope	0.160**	0.072	0.044**	0.020
Observations		422			
Log-Likelihood		−204.68			
LR Chi2(20)		136.22			
Prob > Chi2		<0.001			
Pseudo R2		0.25			

Note: *, **, and *** represent $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively.

Further, Table 6 indicated that weather and soil characteristics played significant roles in farmers' decisions. Farmers with fields located in drier areas were more likely to adopt DCR practice. Suppose all the other variables are fixed at the sample average, if precipitation decreases by 1 mm, then producers would be 0.3% more likely to adopt DCR practices. This trend was also clear in Fig. 1 where DCR adoption rate was greater on the west end of the study region, as illustrated by increasing dominance of green colors when moving from east to west. Low precipitation and the associated water shortage negatively affect corn yield (Lobell et al., 2013; Bowles et al., 2020). In contrast, more diverse rotations could positively affect crop yields, especially under unfavorable weather conditions, and this may explain farmers' DCR adoption decisions in such regions.

In addition, AWC also negatively affected DCR adoption decisions. Producers would be 5.3% less likely to adopt DCR when AWC increases by 1 percent. The enhanced likelihood of DCR adoption in the regions with less water availability was likely because more complex crop rotations could increase soil water storage through increasing soil organic matter and infiltration rate, thereby serving as an adaptive approach for farmers in the regions facing soil moisture deficit (Basche et al., 2016; Rawls et al., 2003). Bulk density is also positively related with DCR adoption decisions, and producers would be 74.1% more likely to adopt DCR practices when bulk density increases by 1 unit. Compared to simplified crop rotation, research has shown that extended crop rotations improve soil structure and lower bulk density (Russell et al., 2006; Liebig et al., 2014). Therefore, DCR could potentially be used by farmers as an adaptation strategy on the soils with higher bulk density.

Similar to Cutforth et al. (2001), we found an increase in slope contributed to a higher adoption likelihood of DCR. As indicated in Table 6, a farmer would be 4.4% more likely to adopt DCR when land slope increases by 1°. Bakker et al. (2005) pointed out that soil erosion could motivate farmers to alter their land use, and that steeper slope, as a contributor to soil erosion, could be a direct driver of land use change. Mulik (2017) also pointed out that in comparison to deep and flat soils, DCR adoption would achieve more benefits on the highly erodible soils. Plant diversification could help reduce soil erosion (Jankauskas et al., 2004; Hunt et al., 2019), therefore providing a feasible solution for lands with steeper slopes to mitigate soil erosion.

3.3. Adopters' ratings on yield and profit consequences of diversified crop rotation (DCR)

Table 7 shows the estimated results for yield and profit change after adopting DCR. Compared to the more recent (<10 years) DCR adopters, early adopters who had used DCR for more than 10 years experienced a greater positive effect of DCR on both yield change and profit change.

It generally takes years before the yield and profit benefits of soil conservation practices start to manifest (Saak et al., 2021). In this regard, a comprehensive synthesis of 11 long-term experiments spanning a

Table 7
Bivariate interval regression estimation results for yield and profit changes after diversified crop rotation (DCR) adoption.

Category	Variables	Yield Change		Profit Change	
		Estimate	Std. Error	Estimate	Std. Error
Farmer Characteristics	Early adopter	2.534**	1.001	3.432***	0.961
	Education	1.128**	0.534	−0.413	0.513
Farm Characteristics and Management	Off-farm	−0.445	0.339	−0.108	0.328
	Sales	0.737**	0.323	0.654**	0.311
	Livestock	0.406	1.101	0.988	1.071
	Organic	7.235***	2.079	3.978**	1.924
Attitude and Perception	New crop profitability	−0.256	0.483	−0.849*	0.469
	Pest cycle	2.104**	0.927	2.025**	0.884
	Fertilizer cut	1.194	0.750	2.159***	0.724
Crop Diversity, Climate and Soil	Crop diversity	0.139	0.103	0.322***	0.099
	Temperature	−0.252	1.039	0.181	1.001
	Precipitation	−0.008	0.018	0.013	0.017
	AWC	−0.053	0.547	−0.045	0.525
	LCC I	0.081	0.068	0.042	0.065
	LCC II	0.034	0.044	0.031	0.043
	SOM	−0.662	3.475	4.485	3.362
	Bulk density	−6.233	9.007	−11.168	8.696
	Slope	−0.802*	0.420	−0.803**	0.405
Observations	271				
Log Likelihood	−564.08				
LR chi2(36)	97.32				
Prob > Chi2	<0.001				
Rho	0.51***				

Note: *, **, and *** represent $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively.

wide east-west precipitation gradient across the U.S. and Canada showed that DCR practice accelerated yield increases over time (Bowles et al., 2020). Using seven long-term experiments spanning a wide latitudinal gradient across Europe, Marini et al. (2020) also found a yield increase in winter cereal immediately after DCR adoption, with the advantage maintained over time, while the yield gain of spring cereal increased over time without leveling off even after 50–60 years. These results suggest that long-term sustained use of DCR will help maximize its benefits.

After DCR adoption, more educated farmers tend to perceive a higher degree of yield increase. Additionally, adopters with higher gross sales were more likely to perceive an increase in yield and profit. Some conservation practices require a sizeable investment cost, and thus larger farms have an advantage due to the economies of scale (Prokopy et al., 2019). Larger farms could spread the upfront investment in DCR related equipment to more acres, thereby managing to reduce the average production cost and improve the profit per acre of land. The results in Table 7 showed that in contrast to conventional farms, organic farms benefited more from DCR adoption in terms of both yield and profit. Specifically, organic farmers perceived a more than 7% increase in yield and nearly 4% increase in profit, when compared with the non-organic farmers. Synthetic fertilizers and pesticides are prohibited in organic production systems to reduce the environmental consequences of food production (Seufert et al., 2017). Therefore, to sustain crop yields, organic farmers may find it necessary to use alternative farming practices such as DCR to control pests and manage nutrients (Barbieri et al., 2017). Even though previously we did not find any difference in adoption decisions between organic and conventional farms, their length and degrees of diversification levels could differ. For example, Barbieri et al. (2017) found that the average rotation length of organic farms was 0.7 years or 15% longer than conventional farms. Similar to our finding, a robust analysis of a larger meta-dataset by Ponisio et al. (2015) also concluded that as a natural pest control and nutrient management practice, DCR helped increase crop yield on organic farms.

Among DCR adopters, the concerns about 3rd and 4th crop profitability had negatively affected the perceived profit change after DCR adoption. Davis et al. (2012) and Hunt et al. (2017) found that the profitability of 3- and 4-year rotations was comparable to that of 2-year rotation when no manure cost was included (assuming manure was produced by on-farm livestock). Their caveat was that the extended rotations might not be as profitable as 2-year rotation if farmers purchased manure instead. Using the same amount of synthetic fertilizer input in both conventional and diversified crop rotations, Singh et al. (2021) found that despite the yield increase for corn and soybeans in the 3- and 4-year rotations, the DCR systems were less profitable than 2-year rotations mainly due to the lower profitability of oat and winter wheat when compared to corn and soybeans. This indicates that the lack of 3rd and 4th crop profitability could pose a challenge to current adopters and may cause them to dis-adopt the practice if the economic disadvantage becomes intensified. Therefore, it is important to increase the 3rd and 4th crop profitability through identifying more profitable crops, expanding market demand for 3rd and 4th crops by including them in livestock feed, creating and promoting crop insurance programs that cover more crops, and offering price and insurance premium subsidies for potential 3rd and 4th crops and to DCR adopters.

Furthermore, Table 7 shows that the adopters with more agreement on the role of DCR in controlling pests and diseases perceived greater positive changes on both yield and profit as a consequence of DCR adoption. Hunt et al. (2017) also found that when compared to conventional herbicide regime, low herbicide regime generated similar corn and soybean yields in the 3- and 4- year crop rotation systems. This indicates that producers who understand DCR's benefit in natural pest control could cut down pesticide use and have a similar or higher yield and profit. Similarly, those who showed more agreement on the role of DCR in reducing fertilizer requirement perceived a greater positive increase in profitability. While DCR coupled with lower fertilizer use could have no significant effect on crop yield when compared with simplified rotation and conventional fertilizer use, the profitability will increase due to reduced fertilizer cost. Furthermore, in regions with higher level crop diversity, producers perceived a higher profit margin, potentially due to improved infrastructure for the diversified crops in such regions. While a steeper slope had increased the odds of DCR adoption (Table 5), it showed a negative influence on the perceived yield and profit changes as a result of DCR adoption. Therefore, the producers on sloped lands could have chosen DCR as an effective control for soil erosion, rather than increasing crop yield and profit.

4. Conclusion

Utilizing farmer survey data, this paper examined determinants of farmers' crop rotation choices in the west margins of the U.S. Corn Belt where a gradual loss in crop diversity has occurred during the past several decades. To help understand the future prospect of DCR usage in this region, we also investigated producers' rated changes in yield and profit due to DCR adoption and impacts of their influencing factors. We found that 35.3% of producers had never adopted DCR, while 7.8% of producers had discontinued the DCR practice. On average, current adopters were implementing DCR practice on 47.8% of their operated acres, and among the current adopters, the majority had used the practice for more than 10 years. Longer usage duration (10+ years) of DCR generated additional benefits among the adopters as shown by its contribution to both yield and profit increase, and producers with 10+ years of experience also used DCR on a higher proportion of their land.

Our findings indicate that producers in our studied region likely regarded DCR as an adaptive strategy to cope with water deficit, improve soil structure, and reduce soil erosion on marginal land. Therefore, instead of promoting DCR on all the farm acres, promotional efforts of DCR practice could specifically target the regions with limited precipitation and easily erodible soils, where conventional crop rotation generates low profits yet incurs significant environmental costs. As DCR acres gradually increase in those regions, new facilities and markets will be built up and developed to accommodate the supply of additional crop varieties. The improvement in infrastructure and newly developed markets could further help farmers in regions with better soil and climate conditions to gain more confidence towards the economic performance of extended crop rotations, therefore scaling up the DCR adoption in more regions.

In addition to climate and soil conditions, other farm management practices such as organic farming and integration of livestock in cropland are important factors that positively affect the adoption decisions and profitability of DCR practice. In this regard, the increasing demand for organic food will help increase the share of organic farms, therefore increasing the necessity of DCR practice on more acres to control pest problems and manage nutrients in a natural way. Furthermore, to effectively promote DCR adoption in the future, re-integration of livestock in the cropping operations is also necessary. DCR and livestock are mutually dependent and beneficial as additional crops in extended rotations could provide livestock feed and in return livestock manure could be readily applied to fields to save fertilizer expenses.

While this study is carried out in the west margins of U.S. Corn Belt, some of our findings bear close resemblance to the studies carried out in other adjacent regions (Cutforth et al., 2001; Roesch-McNally et al., 2018; Wang et al., 2019). Therefore, we can infer that profit and biophysical considerations affect producers' DCR adoption decisions on a broad scale. Our results suggest that both technical and policy support are needed to help farmers use extended crop rotations for the first couple of years until its benefits are well-manifested. For example, research experiment could be carried out to provide producers with useful information, such as recommendations on economically sustainable 3rd and 4th crops in the local region, optimal adjustment of herbicide and fertilizer usage in extended crop rotations to enhance profitability, and so on. To help small and financially constrained farmers adopt the practice, investment loans or subsidies on specialized equipment should also be readily available. Finally, to scale up DCR adoption, especially on well-conditioned crop land with flat slope and deep soils, it is necessary to provide DCR users with additional financial support, such as subsidies for DCR practice, crop price subsidies, reduced insurance premiums, and affordable insurance coverage for new crops to reduce risks and increase profitability.

Credit author statement

Tong Wang: Funding acquisition, Conceptualization, Investigation, Formal analysis, Writing – original draft; Hailong Jin: Methodology, Software, Formal analysis; Yubing Fan: Conceptualization, Writing – review & editing; Oladipo Obembe: Data curation, Conceptualization; Dapeng Li: Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Bivariate probit regression estimation results for yield and profit change after diversified crop rotation (DCR) adoption

Category	Variables	Yield Change		Profit Change	
		Estimate	Std. Error	Estimate	Std. Error
Farmer Characteristics	Early adopter	0.281	0.173	0.515***	0.175
	Education	0.112	0.093	−0.053	0.092
Farm Characteristics and Management	Off-farm	−0.094	0.059	−0.003	0.059
	Sales	0.146**	0.057	0.120**	0.057
	Livestock	0.231	0.191	−0.129	0.192
	Organic	0.825**	0.367	0.234	0.335
Attitude and Perception	New crop profitability	0.022	0.086	−0.138	0.086
	Pest cycle	0.472***	0.167	0.369**	0.161
	Fertilizer cut	0.172	0.132	0.361***	0.134
Crop Diversity, Climate and Soil	Crop diversity	0.030*	0.018	0.050***	0.018
	Temperature	0.089	0.178	0.201	0.181
	Precipitation	−0.003	0.003	0.001	0.003
	AWC	−0.025	0.095	−0.053	0.097
	LCC I	0.015	0.012	0.010	0.012
	LCC II	0.003	0.008	0.003	0.008
	SOM	0.411	0.599	1.637**	0.639
	Bulk density	1.171	1.645	−1.348	1.585
	Slope	−0.112	0.073	−0.054	0.075
Observations	271				
Log Likelihood	−297.12				
LR chi2(36)	80.89				
Prob > Chi2	<0.001				
Rho	0.63***				

Note: *, **, and *** represent $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively.

Table A2
Correlation matrix of CDL crop layer, weather and soil variables matched with survey data (N = 614)

	Crop diversity	Temp.	Prec.	AWC	LCC I	LCC II	SOM	Bulk density	Slope
Crop diversity	1								
Temp.	−0.11***	1							
Prec.	−0.38***	0.28***	1						
AWC	−0.19***	0.39***	0.30***	1					
LCC I	−0.34***	0.08**	0.64***	0.13***	1				
LCC II	0.08**	0.34***	−0.15***	0.47***	−0.40***	1			
SOM	−0.17***	−0.50***	0.02	0.27***	0.19***	−0.02	1		
Bulk density	0.06	0.18***	−0.08**	0.41***	−0.17***	0.29***	0.19***	1	
Slope	0.14***	−0.00	0.18***	0.17***	−0.11***	−0.27***	−0.12***	−0.01	1

Note: *, **, and *** represent $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively.

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