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Why do farmers stop using collective drip irrigation technology? Evidence from rural Xinjiang, China

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ABSTRACT

Collective drip irrigation (CDI) technology is becoming increasingly important for saving water and fertilizer and for improving land productivity. However, many farmers stop using this technology after investing in it and using it for several years in China. Sizable transaction costs occurring in CDI management may play a major role in CDI usage, but little research has been conducted to date. This paper measured transaction costs in traditional and new methods. Empirical estimates of the effects were obtained by applying Heckprobit and probit models to data collected in Awat County, Xinjiang, China, in 2017. We find that (1) new transaction cost proxies related to employing/demising irrigators and checking outcomes of irrigation and fertigation have significantly positive effects on the use decision of CDI and that (2) the traditional transaction cost proxy related to group size has a U-shaped relationship with the probability of using CDI, while the proxy related to social heterogeneity has significantly negative effects on this probability. These findings suggest that transaction costs originating from uncertainty are an important factor in limiting the use of this technology. Additionally, this paper contributes to the literature by examining the relationship between transaction costs and collective action.

1. Introduction

Compared with rain-fed farming, irrigated agriculture contributes a greater share to global food production (UN-Water, 2012) and has positive effects on rural incomes and diversification (Li et al., 2020). However, irrigated agriculture is responsible for 70 % of the world's freshwater withdrawal (FAO, 2007). Given the increasing water demand for nonagricultural purposes, the amount of water available to develop irrigated agriculture is becoming increasingly limited (FAO, 2007; UN-Water, 2012). To reduce water use in irrigated agriculture, drip irrigation technology is becoming an increasingly important strategy, as it can contribute to major water savings, particularly in developing countries. In 2017, 66.9 % of the area covered by this type of irrigation was located in developing countries (International Commission on Irrigation and Drainage ICID, 2018).

Drip irrigation technology is used not only by individual households but also in collective systems that involve multiple households (Kuper et al., 2009; Errahj and van der Ploeg, 2017). Despite the large water savings potential, the available evidence shows many cases in which small holders (private or collective) stopped using drip irrigation systems after investing in them and using them for several years (e.g., Kulecho and Weatherhead, 2005; Ortega-Reig et al., 2017). In the case of private systems, factors such as unreliability, inadequate or low-quality irrigation water, lack of technical support and irrigation management knowledge, unavailability of replacement parts, and limited yield increases have been found to play a role in decisions to stop using these systems in Kenya and Zimbabwe (Kulecho and Weatherhead, 2005; Belder et al., 2007). Little research has been conducted on the reasons why farmers stopped using collective drip irrigation (CDI) systems. An exception is the study by Ortega-Reig et al. (2017) on the Acequia Real del Júcar and the Júcar–Turia Channel in Spain. This study revealed that problems and conflicts related to modifying collective irrigation schedules, collective fertilisation and the need to monitor infrastructure were major factors explaining why farmers no longer used the system.

CDI is a form of community-managed irrigation where farmers act as both users and managers. This model is prevalent not only in China but also in various other regions worldwide, including Tunisia,

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Mozambique, Ethiopia, Bolivia, Ecuador, Cambodia, Nepal, and Spain (Bastakoti and Shivakoti, 2012; Saldias et al., 2012; Ferchichi et al., 2017; Berhe et al., 2022; Hoogesteger et al., 2023). These programs are referred to by different names, such as "community-managed irrigation systems" or "farmer-managed irrigation systems," and not all of them utilize drip irrigation technology. Nevertheless, the underlying theme of the studies of these systems is consistent: the impact of farmers' collective involvement in irrigation management on the outcomes of the irrigation systems.

The focus of studies in this field, as well as our study, is the interplay between institutions and infrastructure. Echoing the views of Coward (1985) and Uphoff (1986), we regard irrigation management as a sociotechnical endeavour where institutional frameworks dictate the performance of technologies. This implies that, in the context of CDI, the decisions made by farmers regarding its use are based on the profitability of CDI as shaped by collective management protocols and infrastructure. When examining the influence of institutions and infrastructure on the adoption of technologies, the transaction costs involved in the collective management of irrigation schemes have often been identified as critical factors in the usage of these schemes. Recent research has indicated that transaction costs can emerge in irrigation management because of the need for collaborative decision-making, oversight of water and system usage, and conflict resolution, all of which can impact the performance of irrigation systems and farmers' behavioural responses to these systems (Ortega-Reig et al., 2017; Bhattarai et al., 2018; Pérez-Blanco et al., 2021). In essence, the impact of transaction costs on farmers' decisions to use CDI is fundamentally related to the intricate interplay between infrastructure and institutional arrangements in irrigation.

However, previous studies have primarily assessed transaction costs in collective water management on the basis of user group characteristics (Ayres et al., 2018). In reality, transaction costs can vary among group members, suggesting that, ideally, they should be measured at an individual level when individual choices concerning collective action are examined. Furthermore, it is crucial to differentiate between farmers' decisions to invest in CDI systems and their decisions to use or discontinue using collective irrigation systems, as different factors may influence these choices. Although transaction costs have been identified as a significant factor in irrigation technology adoption decisions (i.e., investment) (e.g., Bhaduri and Manna, 2014; Hunecke et al., 2017), there has been limited research on their role in decisions to use or cease using CDI and other collective water-saving irrigation systems.

In fact, the water-saving potential of drip irrigation hinges on farmers' proper long-term usage, which necessitates low transaction costs to gather and apply pertinent information and contextual knowledge to make optimal irrigation and fertigation decisions. Therefore, understanding the role of transaction costs in usage decisions is vital for the effective management and utilization of CDI systems and other community-managed irrigation systems to prevent unforeseen outcomes such as discontinuation of use or increased water consumption to offset rising transaction costs and production costs. To address this gap, the research presented in this paper investigates the effects of individual- and group-level transaction costs associated with CDI management on farmers' decisions to continue or discontinue the use of CDI technology. This contributes to a deeper understanding of the substantial interaction between infrastructure and institutional arrangements in irrigation.

We focused on CDI systems in Awat County in the southern Xinjiang Uyghur Autonomous Region, P. R. China. Xinjiang is a semiarid, drought-prone province in China (Fig. 1). The share of water resources used in agriculture amounts to 94.3 % (Department of Water Resources of Xinjiang Uygur Autonomous Region, 2017), and its CDI area is the largest among all province-level administrative regions in China (Ministry of Ecology and Environment and National Bureau of Statistics China, 2017: Table 2–6; Ministry of Water Resources China,2017). As a large share of the farmers in Awat County who have invested in CDI have stopped using it (Agriculture Bureau of Awat County, 2015), it makes the region an interesting case study for our research. A survey dataset collected in 2017 from 697 households living in 17 villages, with 200 households having access to 39 CDI systems, was used for the empirical analysis. Given that similar problems with the use of collective water-saving irrigation systems are not limited to Xinjiang (e.g., Adams et al., 2021; Cai et al., 2022), the insights obtained from this study are expected to be relevant for policies aimed at improving the use of collective water-saving irrigation technologies in other regions inside and

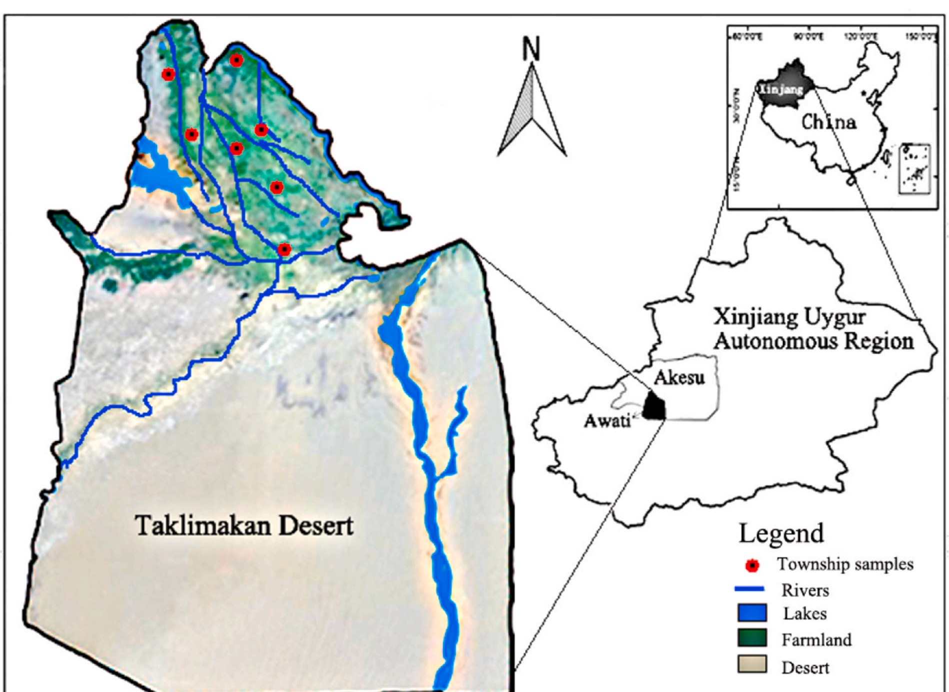

Fig. 1. Map of the study area in southern Xinjiang, China.

outside of China.

The rest of the paper is structured as follows. Section 2 presents our theoretical consideration of the relationships between transaction costs and farmers' decisions to use CDI Section 3 introduces information on CDI projects and their management in Awat County. Section 4 presents the estimation strategy, including the empirical model and variable specifications. Section 5 describes the data collection methods. Section 6 presents and discusses the estimation results, and concluding remarks are presented in Section 7.

2. Theoretical considerations

Mainstream economics has evolved to incorporate the insights of new institutional economics, leading to a more nuanced understanding of the roles of transaction costs and transformation costs in comparing decision options (Marshall, 2013). New institutional economics posits that the institutional context shapes the decision-making process by defining the potential benefits and costs associated with decision options. However, this influence is affected by information asymmetry regarding these potential benefits and costs, as well as other considerations not explicitly covered by the institutional arrangements in place. This implies that decision-makers must gather information, bargain among stakeholders, monitor performance, balance the benefits of the rules, and suffer from potential losses caused by information asymmetry and unsettled considerations (Vatn, 2005). Therefore, echoing the views of Williamson (1975, 1985, 1996), we regard transaction costs as encompassing the time costs involved in obtaining more and better information and the possible losses caused by inferior decisions (cited by Rindfleisch and Heide, 1997).

In the case of CDI, all of this originates from the uncertainty associated with CDI management, which sets off a chain of events that impact group decision-making and outcomes. To carry out CDI management tasks collectively, farmers must exchange information among themselves and possess relevant contextual knowledge that is more specific than the ability to apply the rules of logic and causality analyses (Downs A, 1957). Additionally, farmers must be prepared to mobilise and to understand a given situation or decision problem (Brezillon and Pomerol, 1999). However, the information and contextual knowledge that individuals have at their disposal are often imperfect (Downs, 1957), leading to uncertainty. For example:

- The farmer may lack knowledge about other farmer–investors' interests in water and nutrition, fertilizer affordability, irrigator candidate preferences and satisfaction with current fertilizers and irrigators.
- The effects of the farmer's own interests, choices or opinions on the joint decisions, or choices made by their group may be uncertain.
- The effects of upcoming group decisions, outcome monitoring and conflict settlement on the utility and profits obtained from applying irrigation water and nutrients to crops may be uncertain.
- The farmer may be unsure about the opportunism of other farmer–investors and irrigators and how such opportunism affects individual utility and profits gained from water and nutrition applications.
- The farmer may not possess all the relevant knowledge to address the problems that arise when using, managing and maintaining CDI systems.

Such uncertainty prompts farmers utilizing a CDI system to make suboptimal joint management decisions, consequently forfeiting some of the anticipated benefits associated with the inputs utilized in crop production, such as land, water, fertilizers, and labour. The critical process of fertigation is considered an illustrative example. Optimal fertigation hinges on farmers having precise information and contextual knowledge regarding the appropriate amount and frequency of fertilizer application for their specific cotton crops within the CDI scenario. Although there are established standards for CDI that offer guidance on the quantity and frequency of fertigation, achieving the best local practice also necessitates a deep understanding of local soil conditions, the specific characteristics of the cotton being grown, and the intricacies of the CDI system itself. Unlike the familiar flooding method, the CDI has distinct technical aspects that require farmers to adapt. Farmers often possess only fragments of this critical information, a situation where such incomplete knowledge can result in either overfertilisation or underfertilisation. Such suboptimal management decisions could lead to lower crop yields, causing significant economic losses for individual farmers. The potential decrease in yields represents a form of avoidable loss that could be mitigated with more comprehensive and accurate information. To address this situation, they have the option to invest time and effort in acquiring information and knowledge that could facilitate more informed decision-making.

Consequently, transaction costs in the management of CDI systems encapsulate the potential losses and time costs that farmers encounter in the cultivation of cotton when utilizing the CDI system. In other words, a farmer with access to CDI will consider these transaction costs an element of the expected net returns in the decision-making process regarding the use of CDI technology. The latent model of the expected net profit satisfies the following:

$$E\pi\left(U_i^*\right) = B_i - FC_i - TC_i \tag{1}$$

where $E\pi\left(U_i^*\right)$ is the i^{th} farmer's expected net profit from CDI use. When $E\pi\left(U_i^*\right)>0$, this farmer is expected to use CDI. B_i is the production value of the CDI, which is the value of the cotton fertigated and irrigated by CDI. The costs involved in using CDI include production costs and transaction costs. FC_i represents the production costs of CDI, such as the management fees, energy costs, water costs, fertilizer costs and pipe costs. TC_i represents the transaction costs related to collectively managing the CDI system.

3. CDI projects and their management in Awat County

Awat County, a semiarid area located at the edge of the Taklimakan Desert in southern Xinjiang, is China's most important production area for long-staple cotton. As of 2015, Awat County had 106 CDI projects, with an average area of 105.8 ha (Agriculture Bureau of Awat County, 2015). However, CDI was not used on 41.8 % of the CDI-equipped farmland in 2015. This nonuse percentage was as high as 72 % in Bex'erik Township and ranged from 54.7 % to 19.1 % in the other six nonurban townships in the county (Agriculture Bureau of Awat County, 2015). Awat Township is not included because it has only urban land.

The CDI projects in Awat County consist of several plots owned by multiple farmer–investors, with plot sizes consisting of hundreds or thousands of Ha. The foundational infrastructure of CDI systems encompasses a water storage facility, a pump unit, a filtration system, a pressure control system, a fertilizer dissolver, (sub)main pipelines and laterals, valves, and drip pipes (as detailed in Guan et al., 2022). The drip pipes of the CDI system are categorized into public and private segments. The public pipes are strategically positioned on the basis of the construction blueprints during the development phase of the CDI project. In contrast, private pipes are purchased and installed on individual plots by farmers and are tailored to their specific cotton cultivation layouts.

In Awat County, the investment decision about the CDI infrastructure is a group decision that involves participating farmers and the local government, as they jointly finance the investment. Initially, village cadres were informed that CDI projects would be built and subsidised (e.g., partial fixed investment, energy use and maintenance costs of CDI projects) in Awat County by a government agency—the Water Resource Bureau of Awat County. The cadres were then ordered to collect information on qualifying farmland and on farmers who would be willing and able to make such investments in their villages. The outcome was reported by the village government to the government agency. The agency selected the CDI projects on the basis of the suitability of the farmland, village-level criteria (including, e.g., the village's history of compliance with policies at different levels, the size of the CDI area and the amount of farmland without CDI in the village) and the annual CDI subsidy amount provided by the central government. After site selection, with the exception of private pipes, the government subsidized all these components, providing an average of 800 yuan per mu. The remaining fixed investment costs, estimated at approximately 200 yuan per mu, were borne by farmer-investors whose farmland was situated within the service area of the CDI project.

In Awat County, the CDI infrastructure is used, maintained and managed collectively by the group of farmers who invest in and use the system. They contract with one or more specialised farmers to serve as full-time irrigators to conduct irrigation, fertigation, and maintenance collectively and uniformly according to the existing group management rules, procedures and decisions.

Farmers who use CDI systems are faced with three main management tasks. First, they participate in group decision-making on irrigation and fertigation before an irrigation season. This involves considering (a) the number and sequence of irrigation and fertigation rounds; (b) the quantities of water and fertilizers distributed in each round; (c) the equality of the distributions of water and fertilizers; (d) the managing of dissatisfaction from the previous season and resolving conflicts related to fertigation and irrigation; (e) the appointment of a representative from the farmer-investor group to gather information from the fertilizer market; (f) the types and quantities of fertilizers to be procured for the CDI project. Once the users of a CDI system have reached consensus regarding the answers to the above considerations, their collective decisions on irrigation and fertigation are finalized. Second, farmers jointly using a CDI system decide on the employment of irrigators. This decision includes determining the number of irrigators needed; setting or modifying the qualification standards; assessing the drip irrigation skills, previous performance and attributes such as competence, benevolence, and integrity of candidates; selecting and employing qualified irrigators and negotiating the management fees, i.e., salary; setting rewards and punishments for irrigators; and dismissing underperforming irrigators. Third, farmer–investors individually monitor the outcomes of the irrigation and fertigation activities carried out by irrigators. Joint decisions on the first two management tasks are made during meetings in which all users of a CDI system participate.

Farmers who use a CDI system must pay management fees and pump-related electricity fees based on the farmer's share of land area irrigated by the CDI system in the total CDI project area. The harvested output of crops fertigated by CDI is owned by individual farmers. Water fees are based on the land area that a farmer cultivates and on the land type, i.e., wasteland or contracted land. Contracted land is assigned by village committees to rural households following the implementation of the household responsibility system, whereas wasteland refers to desert land converted to arable land by farm households or the local government (Rao et al., 2016). There are no subsidies for the use and annual maintenance of CDI, and no formal monetary punishment is imposed if a farmer stops using CDI in Awat County.

4. Model specification

The impact of transaction costs on a farmer's decision regarding CDI usage is influenced by the dual considerations of the time spent gathering information and the advantages gained from such information in mitigating potential losses. According to community-based natural resource management theory, larger and more diverse communities require more time to gather information, which also increases the costs of collecting that information. Nonetheless, this observation encapsulates merely a segment of the overarching narrative. Poteete, Marco (2010) posited that face-to-face communication to exchange information has the potential to alter individuals' expectations regarding the behaviour of their peers. This implies that face-to-face communication may embody the beneficial outcomes of information collection. Therefore, in the fourth section, we explain our method for understanding the two main impacts of transaction costs. First, we examine how information costs affect farmers' use decisions of CDI by applying the size and diversity of the user group as indicators of transaction costs. Next, we examine how the outcomes of information collection affect decisions by using the frequency of fertigation and irrigation meetings as other indicators of transaction costs.

4.1. Transaction cost measurement and specification

4.1.1. Group-level transaction cost variables

In studies on collective action, the size and heterogeneity of a user group are generally used as proxies for transaction costs, such as monitoring and negotiation costs (Agrawal and Goyal, 2001; Ayres et al., 2018). Ayres et al. (2018) provided evidence that the number of persons involved in contracting and the degree of heterogeneity in their payoffs are positively correlated with the transaction costs involved in the collective adoption of groundwater control. Following this literature, we used group size and heterogeneity as group-level proxies of the transaction costs involved in CDI use.

While a larger group has more resources (e.g., labour, time, funds) to reduce free-riding through monitoring and punishment, it also has more people to monitor. Therefore, group size may have a nonlinear pattern of collective action in monitoring because of the two opposing forces (Yang et al., 2013). In our case, there are also two opposing forces. The underlying argument is that transaction costs are assumed to be positively related to group size because greater time costs are spent on information collection among more people with imperfect information. However, CDI has properties of decreasing collective production costs for water, fertilizers and labour relative to the group size. On the basis of Eq. (1), the combined effect of group size may form a nonlinear pattern. To examine potential nonlinearity in the effect of group size-related transaction costs, we also added the square of group size to the model. We used the number of users included in a CDI project as the indicator of group size.

Sources of heterogeneity can be diverse and may be categorized into social, cultural and economic heterogeneity (Poteete and Ostrom, 2004; Bardhan and Dayton, 2002). Social heterogeneity not only complicates communication and coordination related to forming and enforcing rules-in-use and increases related transaction costs (Meinzen-Dick et al., 2002; Takayama et al., 2018), but it may also prevent the formation of trust, which reduces transaction costs (Ostrom and Walker, 2003). In the region of our case study, every CDI user group consists of multiple village groups, the most basic social unit in rural China. Users living in the same village group have many opportunities for face-to-face communication, which can facilitate information collection and trust building in their daily lives, including collecting CDI management-related information and enhancing contextual knowledge. Therefore, we apply the number of village groups included in a CDI user group as an indicator of social heterogeneity, which is expected to have a negative effect on the probability of using CDI.

Cultural heterogeneity may hamper the development of trust or lead to different understandings of the most pressing management issues (Poteete and Ostrom, 2004). While ethnic difference is a traditional indicator of cultural heterogeneity (Poteete and Ostrom, 2004), the Uyghur and Han Chinese together constitute 99.2 % of the population in Awat County and were the only ethnic groups observed in the survey. Nonetheless, significant differences exist in terms of language, religion and other aspects between the two groups, and these differences are expected to affect the use of CPR, including the CDI system examined in this study. With respect to cultural heterogeneity, we used the same measure of sociocultural heterogeneity as Varughese (1999):

$$A = 1 - \sum_{i=1}^{n} (p_i)^2$$

where p_i is the proportion of the total group population in the ith ethnic group, in which n=2, i=1 if the ethnic group is Uyghur and i=2 if the ethnic group is Han. This indicator thus varies from 0 to 1. In essence, it measures the probability that any two users from a user group will be from the same ethnic group. We expect that this indicator will have a positive effect on the probability of using CDI.

Economic heterogeneity is indicated by endowment and income heterogeneity. Owing to data limitations, we examined only the role of endowment heterogeneity given that high degrees of endowment heterogeneity have been found to reduce levels of participation in common management (e.g., Gebremedhin et al., 2004). When a CDI project area is allocated by more farmers, the endowment heterogeneity of this project is greater and results in a low probability of using CDI through reducing the possibility of collective action. The underlying argument is that wealthy elites who hold large farmlands in a CDI project and have a relatively large economic interest in the resource can afford to invest extra effort in initiating and maintaining collective action because they will benefit most from sustainable collective management of the resource (Nagendra, 2011; Zhang et al., 2013). On the other hand, it may be argued that small users, defined as farm households with per capita land less than half of the average level of the CDI project, with a relatively small economic interest in water resources are less likely to spend extra effort in the sustainable use of resources given that the use of irrigation water by households in a CDI project is closely related to their land endowments.

4.1.2. Household-level transaction cost variables

Conventional group-level indicators of transaction costs do not consider these within-group differences. Within the same user group, differences may exist between users regarding the levels of information and contextual knowledge about CDI management, which may affect their decisions regarding the use of CDI. In Awat, the CDI user group organizes formal meetings designed to provide the necessary information and knowledge for CDI users. The information acquired through these meetings can lead to a reduction in potential losses for the users while also increasing time costs. Thus, the frequency of attending these meetings embodies the dual nature of transaction costs, reflecting both the mitigation of potential losses and the investment of time. We used a farmer's frequency of attending group meetings on irrigation, fertigation and selecting irrigators and the frequency of outcome monitoring as household-level indicators of transaction costs incurred in CDI system management. Such frequencies are assumed to capture the two sides of transaction costs. On the one hand, a higher frequency means greater information gain, which results in reduced possible losses. On the other hand, a higher frequency means that more time is spent on information gain. Hence, this frequency, which serves as a proxy variable for individual-level transaction costs, exerts an ambivalent influence on the likelihood of using CDI technology.

Information on household-level transaction cost variables was requested for the year 2015, given that they are expected to explain CDI use in 2016. If a household did not use CDI in 2015, the questions were asked for the last irrigation season in which the household used CDI and used it as a transaction cost indicator. The expected signs for these household-level indicators are indeterminate. Attending more group meetings and more frequent outcome monitoring reduce the opportunity costs of making inferior decisions, but they also increase the opportunity costs of the time spent on CDI management tasks. Whether the net impact of these household-level indicators on CDI use is positive or negative is an empirical matter.

Some household characteristics may directly affect the decisions on attending group meetings or monitoring the outcomes as well as the decision to use or stop using CDI. We manage this potential endogeneity by using a method similar to that employed by Mullan et al. (2011). This method proxies the transaction costs by taking the mean value of the variable representing those costs for the other survey respondents within the same CDI project. It assumes that the transaction costs experienced by different farmers within the same project are highly correlated. The average transaction costs of the other surveyed farmers within the same project are therefore expected to reflect the transaction costs of an individual farmer, but the project's value evidently does not depend on the characteristics of that farmer's household.

In the empirical analysis, we performed separate analyses for the three group-level transaction cost indicators, the four household-level transaction cost indicators, and all seven indicators together. This allowed us to identify the impact of adding household-level transaction cost indicators to conventional group-level indicators and to test the robustness of the findings for the household-level indicators.

4.2. Control variables

We employed the socioeconomic system (SES) framework (McGinnis and Ostrom, 2014) to select the control variables. The SES framework is based on a review of the existing knowledge regarding factors that influence collective action in CPRs.

Previous studies on the adoption of irrigation technologies have shown that human capital type and machinery (e.g., education, age, gender, farming experience, household size, and labour availability), natural and physical capital (e.g., farm size, land ownership, soil quality, crop type, and machinery), social and institutional variables (e.g., subsidies, technological advice, crop prices, and irrigation water prices) and risk preferences are important factors affecting adoption decisions (Abdulai and Huffman, 2014; Genius et al., 2013). Following the SES framework, we grouped these factors into actor, resource unit and resource system characteristics (Table 1). We did not include factors related to governance systems, given that the survey was held in a relatively small and homogenous region.

Several actor characteristics were included in the model. The age of the farm household head is intended to reflect the farming experience and physical power of the head of the household. The signs of its effects on the probabilities of having CDI access and using CDI are indeterminate. The educational level of the household head is expected to have a positive effect on both CDI investment and CDI use, given that education stimulates the cognitive ability of farmers and others (e.g., Farmer et al., 1995), thereby increasing the awareness of the advantages of CDI. The gender of the household head may play a role given differences in physical power or other relevant factors between the sexes. The sign of its effect is unclear *a priori*. A dummy variable that equals one for farm households with a head belonging to the Uyghur ethnic group was included in the model to examine whether language, cultural or other differences between Uyghur and Han play a role in CDI investments and use, controlling for household heads' educational levels. The direction of its impact is indeterminate. Labour availability was measured by the number of household members who could perform full-time farm activities. A shortage of labour is expected to encourage a farm household to invest in and use CDI because it reduces labour given that irrigation and fertigation are carried out by irrigators and that drip irrigation generally reduces the time spent on weeding. The number of plots was included in the model as an indicator of the degree of farm fragmentation. No questions about total farm size were asked in the farm household survey because land rights are allocated according to household size, therefore, land markets are virtually absent in the region. We expected that, controlling for labour availability, households with more plots are more likely to invest in CDI and to use it as a way of reducing the labour input per unit of land. Household wealth was measured by the present value of the durables possessed by a farm household, including agricultural machines and devices, livestock, houses, electronic instruments, furniture and transportation vehicles, and is expected to have a positive effect on CDI access and use because wealthier households

Table 1
Variable definitions and expected effects.

	Variable name	Investment impact	Use impact	Description
Dependent variables	CDI use	N/A	N/A	Farm household used the CDI in 2016 (1="yes"; 0="no")
	CDI investment	N/A	N/A	At least one piece of farmland has CDI access (1="yes"; 0="no")
Household-level transaction costs indicators	TC—fertigation	N/A	+/-	Frequency of attending discussions about fertigation[a]
	TC—irrigation	N/A	+/-	Frequency of attending discussions about irrigation[a]
	TC—irrigator	N/A	+/-	Frequency of attending discussions about irrigator-selection[a]
	TC—monitoring	N/A	+/-	Frequency of identifying the outcomes of irrigation and fertigation[a]
Group-level transaction costs indicators	group size	N/A	+/-	Number of households that invested in the same CDI project (unit:100 households)
	group size^2	N/A	+/-	Square of group size
	social heterogeneity	N/A	-	Number of village groups included in a CDI project
	cultural heterogeneity	N/A	+	Probability that any two users from a user group will be from the same ethnic grouping
	endowments heterogeneity	N/A	+/-	Proportion of farm households with per capita land less than half of the average level of the CDI project
Actor characteristics	age	+/-	+/-	Age of the farm household head
	education	+	+	Education level of the farm household head (1= "illiterate", 2= "primary school", 3= "junior high school", 4= "senior high school" (including technical secondary school), and 5= "undergraduate and above" (including junior college))
	gender	+/-	+/-	Gender of the farm household head (1="male"; 0="female")
	ethnic dummy	+/-	+/-	Ethnic background of the farm household head (1="Uyghur"; 0="Han")
	labour availability	-	-	Number of labourers aged 16–65 years old who can engage in full-time farming
	number of plots	+	+	Number of plots cultivated by the household
	wealth	+	+	Value of fixed assets (unit: 10,000 CNY[b])
	risk preference	+	N/A	Agreement of respondent with the statement, "If a new technology is demonstrated to be very profitable but has a possibility of losing money, I will invest in it even if I am short of money" (1–10 scale, "1"= risk averse to "10"= risk taking)
	trust towards the village cadres	+	N/A	Agreement of respondent with the statement, "The village cadres can be trusted" (1–10 scale, "1"=total distrust; "10"= total trust)
Resource unit characteristics	number of wells	+	+	Number of wells owned by all villagers
	distance to county seat	-	-	Distance from the village to the Awat County seat (unit: km)
Resource system characteristics	energy fee	N/A	-	Average unit energy costs used to pump water in the CDI projects of a village (Yuan/mu)
	management fee	N/A	-	Average unit management costs used to hire irrigators in the CDI projects of a village (Yuan/mu)
	CDI age	N/A	-	Age of the CDI project
	noncotton planting period	N/A	-	CDI project is in the noncotton planting period

(continued on next page)

Table 1 (*continued*)

	Variable name	Investment impact	Use impact	Description
				(1="yes"; 0="no")
	CDI land ratio	+	N/A	Percentage of CDI project area in the village farmland area

Note: + stands for positive impact; − stands for negative impact; +/− stands for ambiguous direction.

[a] : For the last irrigation season before 2016, in which the household used CDI

[b] : 1 CNY= 0.14535 USD (as of 14 February 2017, when the survey started).

have more resources to invest in CDI and to pay for using it. Finally, risk preference for investing in a new technology and trust in village cadres were included in the equation explaining the CDI investment decision. Perceived risk related to a new technology has generally been found to be an important factor affecting farmers' adoption of that technology (Baerenklau and Knapp, 2007; Purvis et al., 1995; Ulu and Smith, 2009). Trust in institutions was found to have a positive effect on the adoption of irrigation technology in Central Chile, supporting the premise that greater trust in the government may lead to the perception of a safer investment horizon (Hunecke et al., 2017). We expect that risk-taking farmers and farmers with greater trust in village cadres are more likely to invest in a CDI system. Some household characteristics that are not included in the model may directly affect trust in village cadres as well as the decision to use or stop using CDI. We used the same method to address this potential endogeneity as we used for the transaction cost variables.

The number of wells and distance to the county seat were included in the outcome and selection functions to represent resource–unit (i.e., water) characteristics. Underground water is an important source of irrigation water in Awat County when surface irrigation water is insufficient or becomes available too late in the season. In such cases, underground water from the wells owned by all villagers is used for irrigation. Underground water therefore serves as a guarantee for the availability of the water supply needed for CDI. Because the quantity of water pumped from a well is limited by quotas, we used the number of wells owned by all the villagers in a village to capture the availability of underground water for CDI. The irrigation sequence of townships and villages is generally based on the distance to the county seat, with nearby townships or villages receiving irrigation water earlier. The number of wells in a village is expected to have positive effects on CDI access and use, whereas the distance to the county seat is expected to have negative effects.

The characteristics of the resource (CDI) are represented by four variables in the CDI use equation. The costs per mu of using CDI, as reflected by the energy and management fees, are expected to have a negative effect on the probability of using CDI. These costs are shared in a CDI project, which means that the number of users affects the fees. Thus, the decision to use CDI may affect the fee values. To avoid potential reverse causality, we included the mean value of these fees in the model. We added the CDI age because older CDI projects are more likely to have broken infrastructure, which may cause farm households to stop using and managing the CDI system. Local soil protection policies prescribe that if cotton has been planted in the same area for four years, farmers must plant other crops, e.g., wheat, that are generally not drip irrigated for three years; then, they can plant cotton again for the next four years. In Awat County, the cotton-planting period starts when the CDI systems are installed and become operational. The model includes a dummy variable that equals one if a CDI project is in the noncotton planting period. Both the age of the CDI project and the noncotton planting period dummy are expected to have a negative effect on CDI use. Finally, the percentage of CDI project area in the total farmland area of a village is included in the selection equation. Farmers living in villages with a relatively large share of land having CDI systems are more likely to have invested in CDI and, therefore. to have CDI access.

In addition to these control variables, township dummy variables were included as explanatory variables in both the CDI access and CDI use equations. They are intended to control for major unobserved factors affecting CDI access and use rates that differ between the seven townships where the survey was administered.

4.3. Estimation method

Farm households that invested in CDI and, therefore, had access to CDI were the focus of the empirical analysis. Some unobserved factors may influence both the investment decision and the use or nonuse of CDI systems. As a consequence, sample selection bias may be present. To test for possible selection bias in a model with a binary dependent variable, we applied a Heckprobit model that includes a selection equation explaining household investment in CDI systems. Three instruments that are assumed to affect CDI investment but not the use of CDI were included in the selection equation. They are indicators of a farmer's risk preference for investing in new technology, trust in village cadres, and the percentage of the CDI project area in the total farmland area in a farmer's village in 2016. The risk preference was measured by asking whether the farmer would invest in a new technology that is demonstrated to be very profitable but carries the possibility of losing money, even if the farmer would be short of money. Trust in village cadres was measured by asking the respondent the degree of agreement with the statement, "The village cadres can be trusted". Village cadres represent the government and are more tangible to farmers than higher-level authorities. Village cadres mainly invest in CDI but rarely in CDI management. For new technology investment, trust in village cadres can be considered an important social capital variable that is likely to affect farmers' decisions to jointly invest in CDI but not affect their actual use of CDI. The probability that a farmer has access to CDI is greater in villages where the CDI project area is relatively large, whereas the decision to actually use the CDI system is unlikely to be affected by the percentage of the CDI project area in the total farmland area. The Heckprobit model was applied to estimate the use decision when the results of the Wald test of independent equations indicated that the null hypothesis of no selection bias should be rejected. In cases where the null hypothesis was not rejected, a probit model was estimated for the use decision.

5. Data collection

The data used for this study were collected via a household survey, a CDI project survey and a village survey administered in seven nonurban townships in Awat County in February 2017. A multiple stratified sampling strategy was used to select the households. By excluding one township located in a suburban area with very few farmers, we first selected the remaining seven townships in the county. Seventeen villages were randomly selected on the basis of a roster of all villages in each township. Notably, the number of villages chosen in each township was based on the total number of villages and the village heterogeneity in terms of land and population size, economic development, and geographic location. The household respondents within each village were randomly selected from a list of household names for each village, and, on average, 12 % of the households in each village were interviewed. Finally, we selected 774 households. Of these households, 35 indicated that they were not involved in farmland cultivation and were excluded from the analysis. CDI projects were randomly selected in each village. Of the 17 selected villages, two did not have any installed-well CDI projects and, hence, were excluded from the CDI project survey. The number of selected CDI projects in a village was based on the total number of CDI projects and their size as well as group size, land tenure, crop type and operation situation. Ultimately, 39 CDI projects were included, accounting for 83 % of the total installed-well CDI projects in the 15 villages. We used the names of the irrigation managers and/or the number of village groups reported in the CDI project survey and in the household survey to match the data. Some households that were surveyed had access to CDI, but the CDI system was not included in the CDI project survey. These 28 households were excluded from the sample. Additionally, we removed 14 observations that had an absolute value more than three times greater than the standard deviation for the mean value of one or more of the household-level transaction cost variables. Ultimately, our sample included 697 households. Among them, 200 had access to CDI, and 497 did not. Of the 200 households that had access, 112 used CDI in 2016, and 88 households did not use CDI in that year.

6. Estimation results and discussion

6.1. Descriptive statistics

Among the farm households surveyed for this research, 28.9 % had access to a CDI system. Slightly more than half of those households with access, 56.0 %, used CDI for irrigation in 2016 (Table 2). This result is consistent with the observation that CDI was not used on 41.8 % of the CDI-equipped farmland in Awat County in 2015 (Section 2). Important differences can be observed in the mean values of some household- and group-level transaction cost indicators between the households using and not using CDI. The mean frequencies of the group meetings on fertigation were significantly lower for the household group that used CDI than for the household group that no longer used CDI in the year before they stopped using it. While households using CDI had a significantly smaller group size and lower social heterogeneity than those no longer using CDI, they had significantly greater endowment and cultural heterogeneity.

With respect to the use or nonuse of CDI, four major differences in household characteristics stand out. Heads of households using CDI were, on average, 4.06 years younger, had 0.37 fewer labourers in the household, were 34 % less likely to belong to the Uyghur ethnic group, and had approximately 85 % greater wealth, on average. The number of wells was almost twice as great in villages where farmers who stopped using CDI were living, while the CDI systems in those villages were much older (8 vs. 4 years), on average. Surprisingly, energy fees were significantly higher in villages where farmers using CDI were living, whereas management fees, on average, were significantly lower. Finally, the CDI land ratio was more than twice as large in the villages where farmers using CDI were living.

6.2. Estimation results for transaction costs

The estimation results are presented in Table 3. For brevity and space in the journal, we focused on the results of the transaction cost variables.

6.2.1. Effects of household-level transaction costs

The LR test results for the Heckprobit model with the four household-level transaction cost variables included, but not the group-level transaction cost variables, indicated that the null hypothesis that the two equations are independent cannot be rejected at the 1 % significance level (chi2(1)=0.00, Prob>chi2=0.9859). Therefore, the probit model was used to estimate the model. The coefficients of correlation for the four transaction cost variables ranged from 0.38 to 0.76, while the mean variance inflation factor (VIF) equalled 4.27. Hence, even though some multicollinearity was present in the mode, the impact on the results for the transaction cost variables is likely to be modest.

All four transaction cost variables were found to be significantly related to the use of CDI. Negative effects were estimated for the fertigation and irrigation variables, whereas transaction costs related to irrigator selection and outcome monitoring were found to have positive effects (Table 3 column 1). These results suggest that the opportunity costs of attending fertigation and irrigation meetings dominated the positive effect of avoiding inferior decisions, whereas the opportunity costs of the time involved in irrigator selection and monitoring the outcomes were more than offset by the improved decision making that

Table 2
Descriptive statistics.

Variable name	All observations (N=697)		With CDI access (N=200)		Without CDI access (N=497)		With CDI access: Using CDI (N=112)		With CDI access: Not using CDI (N=88)		Means difference with vs. without CDI access	Means difference using vs. not using CDI
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.		
CDI access	0.289	0.453	-	-	-	-	-	-	-	-	-	-
using CDI	-	-	0.560	0.498	-	-	-	-	-	-	-	-
TC—fertigation	-	-	1.239	0.940	-	-	1.147	1.428	1.712	2.140	-	−0.565**
TC—irrigation	-	-	1.856	1.192	-	-	1.985	1.797	2.136	1.972	-	−0.151
TC—irrigator	-	-	1.298	0.826	-	-	1.478	1.278	1.439	1.251	-	−0.039
TC—monitoring	-	-	3.212	2.075	-	-	3.583	3.098	3.693	3.368	-	−0.110
group size	-	-	0.800	0.451	-	-	0.547	0.245	1.123	0.447	-	−0.576***
social heterogeneity	-	-	2.073	0.808	-	-	1.732	0.803	2.507	0.574	-	−0.775***
cultural heterogeneity	-	-	0.102	0.168	-	-	0.177	0.189	0.007	0.047	-	0.170***
endowment heterogeneity	-	-	0.216	0.231	-	-	0.242	0.195	0.183	0.267	-	0.059*
age	47.35	13.29	46.35	12.71	47.75	13.51	44.56	11.39	48.63	13.95	−1.401	−4.062**
education	2.532	0.748	2.560	0.793	2.521	0.730	2.616	0.852	2.489	0.711	0.039	0.127
gender	0.935	0.246	0.960	0.196	0.926	0.263	0.973	0.162	0.943	0.233	0.034*	0.030
ethnic dummy	0.865	0.342	0.730	0.445	0.920	0.272	0.580	0.496	0.920	0.272	−0.190***	−0.340***
labour availability	2.720	1.313	2.860	1.307	2.664	1.313	2.696	1.114	3.068	1.499	0.196*	−0.371**
number of plots	4.197	2.559	4.885	2.780	3.920	2.412	4.786	2.954	5.011	2.553	0.965***	−0.225
wealth	11.55	11.20	14.90	15.58	10.21	8.511	18.60	18.94	10.19	7.568	4.688***	8.403***
risk preference	5.947	3.789	5.455	3.891	6.145	3.732	5.759	3.844	5.068	3.939	−0.690**	0.691
trust towards village cadres	9.104	1.488	9.003	1.462	9.145	1.498	8.973	1.509	9.040	1.407	0.142	0.067
number of wells	6.516	8.438	8.170	9.726	5.851	7.772	5.893	7.792	11.07	11.13	2.319***	−5.175***
distance to county seat	15.26	8.337	15.35	4.852	15.23	9.385	15.33	4.447	15.37	5.350	0.118	−0.043
energy fee	-	-	8.342	9.140	-	-	11.91	8.116	3.806	8.361	-	8.099***
management fee	-	-	19.18	6.980	-	-	16.26	3.987	22.90	8.138	-	−6.636***
CDI age	-		5.955	2.951	-	-	4.054	2.445	8.375	1.307	-	−4.321***
noncotton planting period	-	-	0.175	0.381	-	-	0.143	0.351	0.216	0.414	-	−0.073
CDI land ratio	0.267	0.299	0.489	0.343	0.178	0.224	0.665	0.331	0.264	0.197	0.311**	0.401***

Note: S.D. denotes standard deviation. ***, **, and * denote that the mean values of a variable are significantly different between the two groups at the 1 %, 5 %, and 10 % testing levels, respectively.

Table 3
Estimation results for the CDI use decision and household- and group-level transaction costs.

	Probit Model(1)		Probit Model(2)		Probit Model(3)	
Variables	**Coef. (Robust std. err[a].)**	**AME.[b] (Delta method std. err.)**	**Coef. (Robust std. err.)**	**AME (Delta method std. err.)**	**Coef. (Robust std. err. a)**	**AME (Delta method std. err.)**
Household- and group-level transaction cost variables						
TC—fertigation	−0.751*** (0.158)	−0.065*** (0.015)	/	/	−0.474** (0.234)	−0.036** (0.015)
TC—irrigation	−0.390** (0.193)	−0.034* (0.018)	/	/	−0.218 (0.386)	−0.016 (0.030)
TC—irrigator	0.872** (0.369)	0.075** (0.036)	/	/	1.354*** (0.458)	0.102*** (0.041)
TC—monitoring	0.663*** (0.143)	0.057*** (0.01)	/	/	0.666* (0.372)	0.050* (0.025)
group size	/	/	−18.097*** (5.292)	−1.596*** (0.379)	−17.425*** (3.746)	−1.312*** (0.273)
group sizeˆ2	/	/	8.700*** (2.383)	0.767*** (0.171)	7.692*** (1.823)	0.579*** (0.129)
social heterogeneity	/	/	−1.204*** (0.325)	−0.106*** (0.026)	−0.110 (0.545)	−0.008 (0.041)
cultural heterogeneity	/	/	−1.326 (1.625)	−0.117 (0.143)	7.751 (4.966)	0.583 (0.353)
endowment heterogeneity	/	/	2.303 (1.506)	0.203 (0.129)	−3.075*** (1.014)	−0.231*** (0.071)
Actor characteristics						
age	−0.015*** (0.004)	−0.001*** (0.000)	−0.012 (0.009)	−0.001 (0.001)	−0.018** (0.007)	−0.001** (0.001)
education	−0.200 (0.159)	−0.017 (0.014)	−0.181 (0.119)	−0.016 (0.01)	−0.197 (0.266)	−0.015 (0.019)
gender	−0.043 (1.241)	−0.004 (0.107)	−0.049 (1.215)	−0.004 (0.107)	−0.048 (1.063)	−0.004 (0.080)
ethnic dummy	−0.902* (0.491)	−0.078* (0.045)	−0.313 (0.899)	−0.028 (0.08)	−0.514 (0.826)	−0.039 (0.064)
labour availability	−0.210* (0.133)	−0.018* (0.010)	−0.151 (0.130)	−0.013 (0.012)	−0.204 (0.162)	−0.015 (0.012)
number of plots	0.111* (0.060)	0.010* (0.005)	0.135** (0.067)	0.012** (0.006)	0.135 (0.085)	0.010 (0.007)
wealth	0.059*** (0.019)	0.005*** (0.001)	0.052** (0.025)	0.005** (0.002)	0.059** (0.025)	0.004** (0.002)
Resource unit characteristics						
number of wells	0.010 (0.023)	0.001 (0.002)	0.127** (0.056)	0.011** (0.005)	0.046 (0.052)	0.003 (0.004)
distance to county seat	−0.066 (0.093)	−0.006 (0.008)	−0.476** (0.228)	−0.042** (0.019)	−0.113 (0.070)	−0.008 (0.006)
Resource system characteristics						
CDI age	−0.454*** (0.083)	−0.039*** (0.004)	−0.707** (0.338)	−0.062** (0.028)	−0.721 (0.175)	−0.054 (0.015)
noncotton planting period	−0.642** (0.325)	−0.055** (0.027)	−1.866** (0.931)	−0.165** (0.074)	−1.401* (0.842)	−0.105* (0.068)
management fee	−0.062 (0.04)	−0.005 (0.003)	−0.197*** (0.076)	−0.017*** (0.006)	−0.271*** (0.095)	−0.020*** (0.007)
energy fee	0.073 (0.056)	0.006 (0.005)	0.309*** (0.131)	0.027*** (0.011)	0.031 (0.031)	0.002 (0.002)
Regional control						
region dummies	Yes		Yes		Yes	
observations	200		200		200	
log pseudolikelihood	−31.720		−32.179		−27.044	
Mean VIFs	4.27		4.38		5.24	
Joint sig. of household-level transaction cost variables	chi2(4) = 236.43 Prob > chi2 =0.000		/ /		$chi^2(4) = 44.15$ Prob > $chi^2 = 0.000$	
Joint sig. of group-level transaction cost variables	/ /		$chi^2(5) = 28.48$ Prob > $chi^2 = 0.000$		$chi^2 (4) = 186.98$ Prob > $chi^2 = 0.000$	

Notes: *, **, and *** denote significance levels of 10 %, 5 %, and 1 %, respectively.
[a] . Std. err. was adjusted for the 7 township clusters.
[b] . The average marginal effect is evaluated under the univariate (marginal) predicted probability of using the CDI.

resulted from it. The latter finding is consistent, for example, with the results obtained by Meinzen-Dick et al. (2018) that communication/discussion helps groundwater users improve their understanding of the negative effects of groundwater overuse and increases the likelihood of collective action in sustainable groundwater use.

6.2.2. *Effects of group-level transaction costs*

The LR test results indicated that the null hypothesis that the CDI investment and CDI use equations are independent cannot be rejected at the 1 % significance level (chi2(1)=0.00, Prob>chi2=0.4824). Therefore, we applied a probit model to estimate the CDI use equation. Excluding group size squared, the coefficients of correlation for the group-level transaction cost variables ranged from −0.39–0.40, whereas the mean variance inflation factor (VIF) was 4.38. Hence, multicollinearity is again modest.

Regarding group size, it is suggested that it has a U-shaped relationship with the probability of using CDI (Table 3, column 3) and that the estimated turning point is located at a group size of 104, which is somewhat larger than the mean group size of 80 CDI users (Table 3). This finding provides evidence that the transaction-cost-increasing effect of increasing group size dominates the positive production-cost-reducing effect for CDI user groups with sizes smaller than 104. For larger groups, the production-cost-reducing effect of group size begins to dominate. Social heterogeneity was found to have a negative effect on the probability of using CDI. This finding provides support for the hypothesis that farmers belonging to CDI systems that involve more village groups face relatively high transaction costs in the management of these systems. When the number of groups increases by one, the probability of using CDI decreases by 0.106, on average. Cultural and endowment heterogeneities, however, were not found to have a significant effect, implying that ethnic diversity and endowment inequality among the CDI system members does not significantly affect a household's probability of using it in the region where we conducted the research.

6.2.3. Effects of household- and group-level transaction costs

We estimated the Heckprobit model to test for possible selection bias. The LR test results indicated that the null hypothesis cannot be rejected at the 1 % significance level (chi2(1)=0.00, Prob>chi2=0.9859). Thus, we applied a probit model to estimate the CDI use equation. Excluding group size squared, the coefficients of correlation for the transaction cost indicators ranged from −0.51–0.76, while the mean variance inflation factor (VIF) was 5.32. Hence, some multicollinearity was present, but it was not extremely high in the model; therefore, this model is used to examine the impact of adding household-level transaction cost indicators to conventional group-level indicators and to test the robustness of the findings for the household-level indicators.

The probit regression results are presented in Table 3, columns 5 and 6. The estimated coefficients for the household-level transaction cost indicators remain jointly significant at the 1 % testing level. This consistent finding provides strong support for the proposition that the time spent by individual households in group meetings and monitoring outcomes of CDI affect a household's decision to use or stop using CDI. As before, attending group meetings on fertigation was negatively related to CDI use, whereas attending meetings on irrigator selection was positively related. The positive coefficient of the frequency of identifying the outcomes of irrigation and fertigation is significant only at the 10 % testing level in the model with both groups of transaction cost indicators, whereas the negative coefficient for attending group meetings on irrigation did not differ significantly from zero in that model. This suggests that the information-cost effect of attending irrigation discussions dominated the positive effect of information gain by attending the discussions, whereas the positive information-gain effect of the time involved in irrigator selection and monitoring outcomes was greater than the negative information-cost effect of this time. Notably, the mean marginal effect of group meetings on irrigator selection is the largest in absolute size in both models, the one with only household-level transaction cost indicators and the one with conventional group-level indicators included. An increase of one in the number of irrigator selection meetings, on average, of 1.3 meetings (Table 2), was found to increase the likelihood of CDI use by 0.–075–0.102, on average.

The estimated coefficients for the group-level transaction cost indicators were also jointly significant. The group size of the CDI system was again found to have a U-shaped relationship with the probability of using CDI and with the estimated turning point located at a group size of approximately 113 (instead of 104 in the model without household-level indicators). However, different results were obtained for some of the other conventional transaction cost indicators after household-level indicators were added to the model. Furthermore, the indicator of social heterogeneity was no longer found to affect the use of CDI, while the indicator of endowment heterogeneity was found to have a strongly significant negative impact after household-level indicators were included in the model. This suggests that greater inequality in land endowments contributes to significantly lower use of the water-saving CDI system. As a result, previous research findings regarding endowment heterogeneity contributing positively to the sustainable use of the CPR should be reconsidered.

6.3. Discussion

Modern irrigation technologies, such as sprinkler or drip irrigation systems, laser levelling of fields, and piped delivery systems, have complex effects on production costs. While they can reduce certain costs, such as labour and fertilizer costs, they also introduce and increase additional costs, such as energy and capital investments in pipes (Graveline, 2016). However, the majority of empirical evidence indicates that these modern irrigation technologies typically result in additional revenue that exceeds the additional costs (Pérez-Blanco et al., 2020;). This incentivizes farmers to increase their water consumption to increase profits, often leading to little or no net water savings from such projects (Pérez-Blanco et al., 2020, 2021). This implies that if water consumption is limited officially or even reduced, farmers may stop using this technology because of little or no additional profit.

China faces significant challenges such as water scarcity, uneven distribution, inefficient utilization, and severe pollution, which are primary constraints on sustainable socioeconomic development. To address these water resource issues and achieve efficient utilization and effective protection, since 2013, in Awat County and various other parts of China, the government has imposed strict regulations on the total agricultural water quota. Moreover, the government anticipates a decrease in the agricultural water quota over the next two decades. To align with the policy of agricultural water reduction, it is stipulated that the government also anticipate a decrease in the irrigated land area in Awat by executing the Grain for Green policy. The current agricultural water quota for Awat County is not sufficient for universal flooding irrigation but is adequate for a certain proportion of it, without being so scarce as to restrict its use to drip irrigation only. This provides farmers with some discretion to opt for CDI on the basis of profitability. Consequently, in Awat County, under the agricultural water quota, farmers are restricted from expanding their irrigated areas or increasing their water consumption, which results in limited revenues from CDI. Therefore, the costs related to CDI usage become important for farmers' decisions to use CDI. To examine these considerations, we focus on and emphasize the role of transaction costs in the use decision, while additional costs, such as manager fees and energy fees, are added into the regression model.

Our study offers new and detailed empirical evidence on how transaction costs, beyond mere production costs, influence farmers' choices following the adoption of modern irrigation technologies. We first analysed the transaction costs arising from the collective management of CDI systems, revealing a poor interaction between existing institutional arrangements and infrastructure. Our findings suggest that transaction costs stemming from uncertainty are a significant factor in limiting the use of CDI systems in Awat County. Consistent with the existing body of literature, we advocate for increased governmental focus on the cost implications associated with the deployment of modern irrigation technologies. However, we particularly underscore the significance of transaction costs that emerge from the inherent uncertainty in collective management practices.

Accordingly, our research yields a dual set of policy implications for future local agricultural practices. As the Chinese government, in its 14th Five-Year Plan (2021–2025), continues to advocate for the adoption of drip irrigation systems, the daily management responsibilities undertaken by farmers are pivotal to the success of ongoing CDI initiatives. Our findings imply that encouraging farmer participation in irrigator-selection meetings and the monitoring of irrigation and fertigation outcomes could decrease the incidence of farmers discontinuing the use of the system. Conversely, optimizing the frequency and efficiency of fertigation meetings may increase farmer engagement with CDI. Second, for the planning of future CDI projects, it is imperative to consider the group size and the diversity of household endowments during the project design phase. Compared with smaller scale projects, projects encompassing a larger number of member households are less likely to be utilized by farmers post establishment. Our research indicates that the average group size for households actively using CDI was 55, whereas the average group size was 112 for those who ceased using CDI (refer to Table 1). This insight can serve as a critical guideline in the strategic planning of new CDI projects. Furthermore, the findings regarding disparities in land endowments indicate that land transfer is essential to prevent farmers from abandoning the use of CDI after project establishment.

7. Conclusion

This paper investigates the influence of transaction costs associated with the collective management of CDI systems on the utilization of CDI. We posit that household-specific transaction costs capture the impact of within-group transaction cost disparities on CDI use decisions, which may not be discernible through conventional group-level transaction cost indicators for common pool resource management. Attendance frequency at meetings focused on irrigation, fertigation, and irrigator selection, as well as the monitoring of outcomes, served as proxies for household-level transaction costs. Moreover, social, cultural, and endowment heterogeneity, alongside group size, were incorporated as indicators of conventional transaction costs. Our findings indicate that (1) attendance at meetings concerning the hiring and dismissal of irrigators, along with the frequency of monitoring irrigation and fertigation outcomes, had significantly positive effects on the decision to use CDI and that (2) the frequency of attending fertigation discussions had a significantly negative effect on CDI use. This suggests that the positive impact of mitigating potential losses by participating in meetings about irrigator selection and by monitoring outcomes outweighs the negative opportunity costs of time expenditure on these activities. Conversely, the avoided losses did not appear to offset the time invested in fertigation discussions. Furthermore, these results imply that transaction costs stemming from uncertainty and varying with each individual farmer are a significant factor in limiting the adoption of CDI systems, in addition to group-level transaction costs. Information gathering and communication among users are widely recommended strategies for reducing transaction costs in CDI management. However, our analysis suggests that the effectiveness of improving governance decisions through communication on fertigation and irrigation may be constrained by the scarcity of affordable information access.

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CRediT authorship contribution statement

Nico Heerink: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Xueqin Zhu:** Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Xiaoping Shi:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Xianlei Ma:** Writing – original draft, Validation, Methodology, Conceptualization. **Changkun Guan:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

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.

Data availability

The authors do not have permission to share data.

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