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ORIGINAL PAPER

From subsistence to market-oriented farming: The role of groundwater irrigation in smallholder agriculture in eastern India

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Abstract
Empowering smallholder farmers in low and middle-income countries (LMICs) and improving their livelihood is a critical goal for poverty reduction. To achieve this, agricultural commercialization can play an important role. However, a prerequisite to achieving agricultural commercialization is access and control of stable irrigation. This study revisits empirically the relationship between groundwater irrigation and crop commercialization. It also analyses the underlying mechanisms of how groundwater affects crop commercialization through on-farm production diversity. Studying the effects of groundwater irrigation on crop commercialization is essential for comprehending the trade-off between agricultural benefits and the environmental costs of groundwater irrigation. Geospatial and remote sensing information, combined with primary household data from small-scale farmers in eastern India, are employed in conjunction with an instrumental variable technique and a 3SLS simultaneous equation model for the analysis. The results suggest that small-scale farmers in eastern India experience enhanced crop commercialization when they have access to groundwater irrigation. Furthermore, the study suggests that the utilization of groundwater irrigation indirectly promotes crop commercialization by incentivizing farmers to diversify their production system.

Keywords Irrigation · Market-oriented farming · Production diversity · India

JEL Classification Q11 · Q13

1 Introduction

Empowering smallholder farmers in low and middle-income countries (LMICs) and improving their livelihood is a critical goal for poverty reduction (World Bank, 2008). To achieve this, agricultural commercialization can play an important role (Barrett, 2008; Muriithi & Matz, 2015; Olwande et al., 2015; Tipraqsa & Schreinemachers, 2009; von Braun, 1995). However, a prerequisite to achieving agricultural commercialization is access and control of stable irrigation. In LMICs, a significant number of farmers continue to depend on rainwater as their main source of irrigation (Steinhübel et al., 2020). Prior research highlights that access to stable irrigation can increase crop yields, improve crop quality, and facilitate crop diversification towards more profitable and high-value crops (Mukherji & Shah, 2005). It can also increase income (Kassie & Alemu, 2021), and improve food security, dietary diversity, and nutrition (Burney et al., 2010; Dillon, 2011; Lipton et al., 2003; Mangisoni, 2011; Mekonnen et al., 2022; Passarelli et al., 2018; Xie et al., 2014; You et al., 2011). While access to irrigation is essential, the type of irrigation facilities, such as groundwater or surface irrigation systems, can also have differential effects on agricultural performance and welfare gains. This article, therefore, reexamines the relationship between groundwater irrigation and crop commercialization. It also empirically investigates the underlying mechanism through which groundwater irrigation affects crop commercialization. Specifically, the study tests the hypothesis: whether improved access to private groundwater irrigation enables farmers to expand their crop choices, leading to enhanced market opportunities and greater financial stability.

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Groundwater irrigation systems such as bore wells and tube wells offer farmers irrigation 'on demand' and are often more predictable and reliable throughout the year, making them more dependable than surface water irrigation which may be affected by seasonal variations and requires infrastructure to transport water to fields (Shah et al., 2003; Smilovic et al., 2015). Moreover, since groundwater irrigation results in significant costs for lifting water, farmers tend to economize on its use and therefore maximize application efficiency (Mukherji & Shah, 2005). Past evidence from the 1960s and 1970s, highlights that groundwater-led irrigation was a key factor in the success of the Green Revolution in northern India (Mukherji, 2022; Pingali, 1997). Groundwater-based irrigation allowed farmers to cultivate crops throughout the year, even during the dry season, resulting in increased agricultural productivity and reduced vulnerability to weather fluctuations. This subsequently increased food security and reduced poverty in northern parts of India (Balasubramanya & Buisson, 2022). Agricultural yields are generally higher in areas irrigated with groundwater than in areas from other sources (Dhawan, 1989; Meinzen-Dick & Mendoza, 1996). This is because an assured water supply encourages complementary investment in fertilizers, pesticides, and high-yielding seeds (Kahnert & Levine, 1993). While the positive relationship between access to groundwater irrigation and agricultural productivity is well-established, excessive use of groundwater can lead to aquifer depletion, land subsidence, saltwater intrusion, and long-term water scarcity, posing serious environmental and socioeconomic challenges (Srinivasan et al., 2015; Steinhübel et al., 2020). Evidence from satellite imagery indicates that regions that have benefitted the most from the Green Revolution in India, are also the regions that are the hotspot of groundwater depletion (Mukherji, 2022; Rodell et al., 2009; Steinhübel et al., 2020).

Using survey data collected from small-scale farmers in eastern India (Odisha) along with satellite data, the study examines the association between groundwater irrigation and crop commercialization amongst smallholder farmers. Studying the effects of groundwater versus surface water irrigation on crop commercialization remains crucial, even in the face of environmental costs, due to its potential to inform balanced and informed decision-making. While the environmental impacts of groundwater overuse are significant, understanding the nexus between irrigation methods and crop commercialization allows us to address both agricultural and sustainability concerns comprehensively. Further, to fully comprehend this relationship and its implications for smallholder livelihoods, the study also delves into the underlying mechanisms. Thus, this paper addresses two key research inquiries: firstly, it explores the potential impact of groundwater irrigation on crop commercialization when compared to surface irrigation systems in eastern India, and secondly, it assesses whether improved water access through groundwater irrigation systems can drive crop commercialization by encouraging on-farm crop diversification. Using an instrumental variable approach and a 3SLS simultaneous equation model, the study establishes a positive relationship between access to private groundwater sources and crop commercialization in Odisha. This effect operates indirectly by increasing on-farm production diversity, thus enabling smallholder farmers to transition towards more market-oriented farming practices. These results underscore the critical significance of groundwater resources in promoting market-oriented agriculture, particularly in regions endowed with abundant water resources. The identification of a positive relationship between groundwater irrigation and crop commercialization implies that policy interventions promoting sustainable groundwater management could foster increased agricultural productivity and market engagement amongst smallholder farmers.

The rest of the article is organized as follows. Section 2 delves into the channels by which groundwater irrigation can influence crop commercialization. Additionally, it provides an overview of groundwater irrigation in India, focusing specifically on the state of Odisha. Section 3 presents the context of the study, while in Section 4, the household survey and geospatial information are detailed, and Section 5 provides an overview of the econometric methods used in the study. The findings are discussed in Section 6, and Section 7 concludes the article by presenting policy recommendations.

2 Groundwater irrigation in India

It is expected that private groundwater irrigation systems such as tube wells and borewells can affect crop commercialization through various pathways. First, private groundwater irrigation systems provide better access and control over water that allows smallholder farmers to grow a wider range of crops that require more water such as fruits and vegetables and other high-value crops that are economically and nutritionally more beneficial (Passarelli et al., 2018). This can help farmers to diversify their income streams and increase their opportunities for crop commercialization. Second, reliable, and consistent water supply using bore wells and tube wells can increase crop yields and improve the quality of crops (Mukherji & Shah, 2005). Thus, higher crop yields can result in higher marketed surpluses, thereby shifting farming from subsistence or semi-subsistence to more market-oriented farming. Third, due to a lack of a consistent water supply, most smallholder farmers in LMICs rely on rainfed agriculture and leave sizable areas fallow during the dry season (Faurès & Santini, 2008). Therefore, groundwater irrigation can support multiple cropping cycles in a year, which can increase production and marketable surplus. Fourth, assured irrigation through tube wells and bore wells can improve the quality of crops, including the size, colour, texture, and nutritional value. This can lead to increased marketability as well as higher prices. As a result, household income, nutrition, and employment prospects for landless workers may increase (Carletto et al., 2017; Domènech, 2015; Khonje et al., 2022; Ogutu et al., 2020; Passarelli et al., 2018; Pingali & Sunder, 2017; von Braun, 1995). Thus, in regions that are abundant in water such as eastern parts of India, Bangladesh, and Nepal, groundwater irrigation can be a powerful way to connect smallholder farmers to markets and therefore improve their welfare (Mukherji & Shah, 2005).

Though utilizing groundwater for irrigation is an appealing solution to counter the unreliability or inadequacy of rainfall, excessive exploitation of groundwater can have profound negative effects on underground water reservoirs. These impacts encompass factors such as the quality and quantity of water, alterations in land elevation, the outflow of water, and the functioning of ecosystems in the surrounding areas (Gleeson et al., 2012; Smilovic et al., 2015; Steinhübel et al., 2020). Over the last few decades, excessive groundwater extraction through private tube wells and borewells has resulted in massive depletion in groundwater levels in a few of the major agricultural states in northern, western, and southern regions of India (Blakeslee et al., 2020; Steinhübel et al., 2020). This situation has arisen due to policies implemented since the late 1960s, which have subsidized electricity, eased the availability of credit for the establishment of groundwater wells and the purchase of pumps, and established food procurement policies that guarantee the procurement of rice and wheat crops (Mukherji, 2022). Furthermore, the rise in local manufacturing of pumps and advancements in drilling techniques, which have led to reduced expenses in setting up groundwater irrigation systems, coupled with decreased input costs attributable to fixed-rate electricity tariffs, have led to the widespread adoption of borewells and tube wells in many parts of India (Steinhübel et al., 2020). Nevertheless, the progress of groundwater irrigation is geographically clustered in specific areas, while substantial portions of eastern India, which incidentally are the most economically deprived regions, continue to rely on rainfed agriculture. Thus, in regions that have abundant groundwater reserves, there is potential for the development of groundwater irrigation. However, it must be considered within the context of sustainable groundwater management.

3 Context of the study

The research was conducted in Odisha, an eastern state in India (Fig. 1), where the economy is largely dependent on agriculture, employing 62% of the workforce. There are three distinct crop cultivation seasons namely: *Zaid* (March to May), *Kharif (*June to September), and *Rabi* (October to February). The state receives 79% of its annual rainfall from the South-West monsoon occurring between June and September. Among these seasons, the *Kharif* period benefits from approximately 73% of the total annual rainfall and holds the utmost significance for farming (Table 2). During this phase, nearly 70% of the entire yearly cropped area is cultivated, while the remaining 20% and 10% are sown during the *Rabi* and *Zaid* seasons, respectively.

Rice is the principal crop grown during the *Kharif* season, while vegetables account for just a small portion of the overall cultivated land (Table 2). Nonetheless, only 30% of the total value of harvested rice is sold in the market, in contrast to most of the produced vegetables being marketed. Additionally, due to the ample monsoon rainfall, a substantial portion of the planted land relies on rainfall, with just 26% being irrigated throughout the *Kharif* season. Given the scanty rainfall during the *Rabi* and *Zaid* seasons, a significant portion of agricultural land remains uncultivated in the study region. Among the crops grown on the remaining cultivated land, vegetables take the lead, accounting for about 70% of the cropped area. Practically all of this vegetable cultivation is supported by irrigation and is intended for the market. On average, during each season, around 10–20% of the value of grown vegetables is retained for household consumption or is wasted.

This trend of large parts of the land area remaining fallow[1] during the dry season (*Zaid* and *Rabi*) is also visible at a more aggregate level (Fig. 2). This is despite Odisha being endowed with an extensive network of rivers and streams. Often land is left fallow to replenish the nitrogen content of soils, and control weeds and other pests. However, in Odisha, irregular rainfall, frequent natural calamities, lack of irrigation facilities, and poor soil quality have resulted in large areas being left fallow (Hoda et al., 2021). Figure 3 shows that almost half of Odisha's districts have less than 20% of their cultivated land covered under irrigation.

As per the latest assessment, Odisha has net dynamic groundwater resources of 16.7 billion cubic meters (BCM), out of which 25 percent has been utilized for irrigation and 5 percent for domestic and industrial use. Additionally, the state has an annual surface water availability of approximately 95.5 BCM, sourced from both within its own boundaries from the inflow of water through interstate rivers from neighboring states (Government of Odisha, 2019). Although the state has a vast potential for irrigation systems,

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[1] Fallow lands include all land that was taken for cultivation but is temporarily out of cultivation. This could include cultivable area, which is kept fallow in the current growing season, or for the last five years.

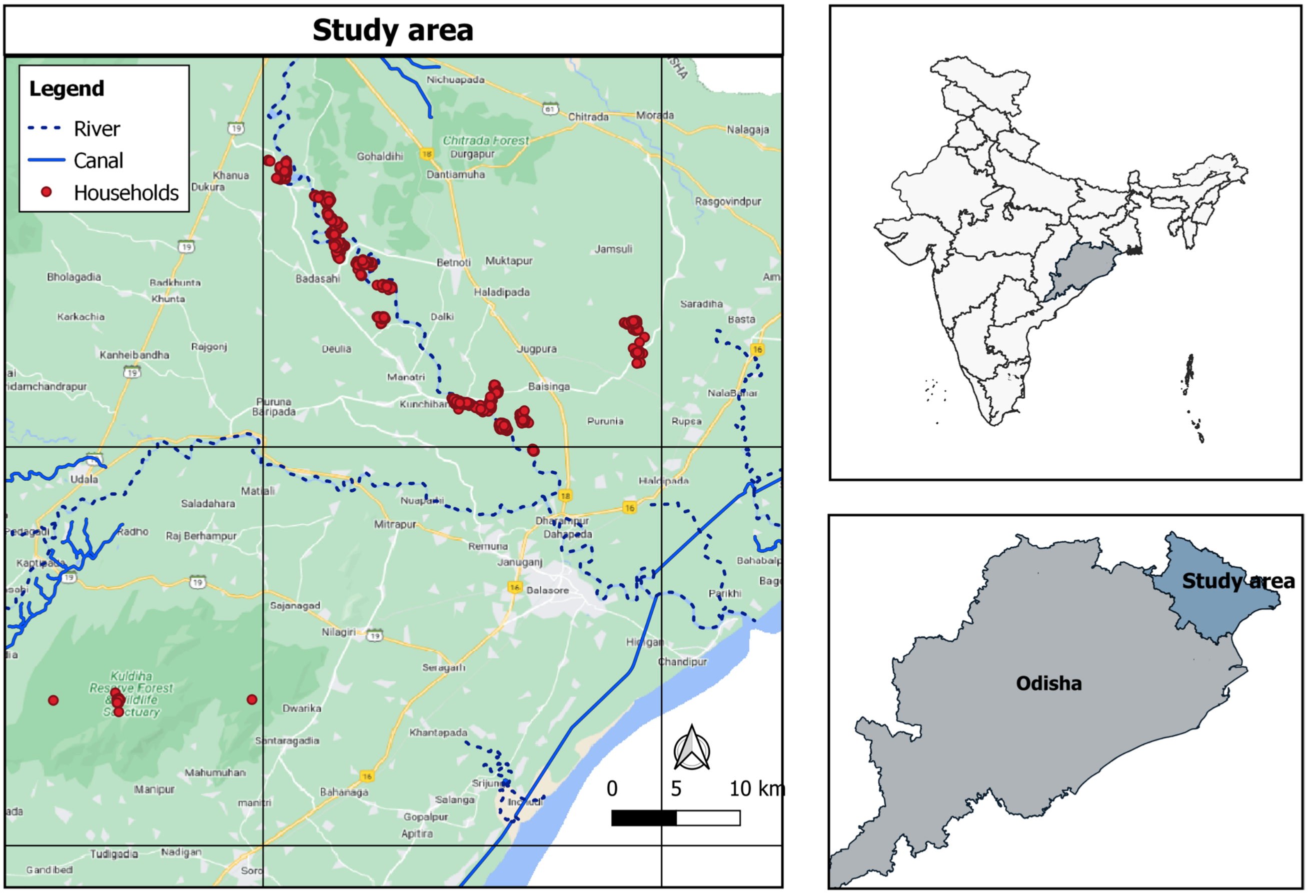


Fig. 1 Study area

the low levels of electrification and sub-optimal quality of electric power make accessing groundwater unaffordable and inaccessible for many smallholder farmers, who mainly rely on diesel-powered irrigation pumps (Hoda et al., 2021; Mukherji, 2022). Moreover, during the dry season, surface water sources tend to diminish or dry up due to reduced precipitation and increased evaporation. Insufficient progress in water resource development and the effective utilization of irrigation capabilities has resulted in diminished agricultural productivity and a rise in uncultivated land during the dry period in Odisha (Hoda et al., 2021). Since the state has relatively high water tables, solar-powered micro-irrigation systems along with initiatives for replenishing groundwater reserves hold the potential to increase access to groundwater in areas where groundwater resources are not yet fully utilized (Agrawal & Jain, 2019; Kishore et al., 2014). Consequently, in 2018, the state Government of Odisha announced the “Soura Jalnidhi Scheme”, which provides subsidies for solar-powered pumps to smallholder farmers. In addition to this program, the centrally sponsored initiative "Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)," launched in 2015, is being executed to increase the cultivated land area under reliable irrigation, minimize water wastage, and enhance water efficiency through the utilization of micro-irrigation methods like sprinklers and drip irrigation.

4 Data and measurement of variables

4.1 Data

4.1.1 Household survey

This study uses primary household data collected between January and March 2019 in two blocks and 20 villages in the Mayurbhanj and Balasore districts of Odisha (eastern India). Figure 1 presents a map of the study area and the location of surveyed households. The primary survey used a structured questionnaire to conduct personal interviews with the person in charge of farm management (usually the household head). The dataset consists of information on the socio-economic characteristics and agricultural activities of the household. To capture all seasons of the year, all agricultural data was collected for a year, from March 2018 to February 2019. Crop production details were compiled separately for the *Kharif*, *Rabi*, and *Zaid* seasons. The survey interviewed 1,105 vegetable-growing households. All households in the sample had access to some form of irrigation for the cultivation of vegetables. 55% of these households used privately-owned irrigation systems such as tube wells or borewells as their only source of irrigation, and 30% did not have any private irrigation systems and therefore relied on community systems such as rivers, canals, tanks, and ponds. The remaining 15% of households used both private and community irrigation systems. Since the study analyses the effects of groundwater irrigation on crop commercialization, it excludes households using both groundwater and surface water irrigation. This helps isolate the specific effect of groundwater irrigation by avoiding confounding factors. In addition to isolating the specific impact of groundwater irrigation, excluding households utilizing both groundwater and surface water irrigation also helps to mitigate potential interactions and complexities that could arise from the combined use of these water sources. Consequently, the group relying exclusively on groundwater irrigation comprises 608 households, while the group utilizing surface water for irrigation comprises 327 households.

4.1.2 Secondary data

Satellite-based land degradation data and Indian soil datasets were extracted from the National Information System for Climate and Environment Studies (NISCES) program by the Indian Space Research Organisation (ISRO). The NISCES land degradation data set consists of information on the fraction of water erosion, wind erosion, waterlogged area, and salt-affected soils within a grid of 5 km × 5 km. This data was generated from the multi-temporal LISS III satellite data from Resourcesat-1 of 2005–06. Further, the Indian soil datasets give information on mean soil organic and inorganic carbon density generated within a grid of 5 km × 5 km.

Rainfall data was extracted from the Center for Hydrometeorology and Remote Sensing (CHRS). CHRS's PERSIANN-Cloud Classification System (CCS) dataset was used which estimates global rainfall in near real-time and at a spatial resolution of 4 km x 4 km. Further, the primary survey data was also linked with geo-tagged data on rural facilities such as locations of block headquarters, agriculture collection centers, Government agriculture markets, etc. provided by the Government of India's Pradhan Mantri Gram Sadak Yojana (PMGSY).

4.2 Measurement of variables

Using data from the household survey collected in Odisha, crop commercialization is measured as the proportion of the gross value of crop output from the sold quantity to the gross value of crop output from the harvested quantity. In other words, it measures the extent to which crops are being sold in the market rather than being solely used for personal consumption or other non-commercial purposes.

The primary focus of the research centers around two key independent variables: access to groundwater irrigation and crop diversification. To measure groundwater access, the study uses a binary variable that represents the use of private bore wells or tube wells as a proxy for groundwater access. In an alternative specification, groundwater irrigation is also redefined as a continuous variable by interacting with the irrigation ratio and whether a household exclusively utilized groundwater for irrigation. Further, crop diversification is measured as a count variable that indicates the number of different crop species grown on the farm during 2018-19.

In the empirical analysis of the association between groundwater access and crop commercialization, as well as the mediation through crop diversification, various factors are considered as controls. These factors include household characteristics, geographical location, and rainfall anomaly. Specific information about each variable can be found in Table 1.

5 Empirical strategy

5.1 Relationship between groundwater irrigation and crop commercialization

5.1.1 Baseline specification

The association between access to groundwater irrigation and crop commercialization is estimated using an ordinary least square approach of the following type:

$$COM_{i,j} = a + \alpha_1\ PIR_{i,j} + \alpha_2'\boldsymbol{H}_{i,j} + \alpha_3'\boldsymbol{G}_{i,j} + \alpha_4 R_{h,j} + \varepsilon_{1,i,j} \quad (1)$$

where, $COM_{i,j}$ is crop commercialization of household i in block j. $PIR_{i,j}$ is a binary variable that takes a value of 1 for all households who used private groundwater irrigation systems such as tube wells and borewells in the period March 2018 to February 2019, and 0 for all those households that used community irrigations systems such as canals, rivers, public tanks, and ponds. $\boldsymbol{H_{i,j}}$ is a vector of covariates that include the socio-demographic characteristics of the household. $\boldsymbol{G_{i,j}}$ is a vector of variables that control for the geographical location of the household to capture the household's access to markets and public services, and access to waterways. $R_{h,j}$ is a variable that controls for deviation in rainfall within a five-kilometer radius of the household during the *Kharif* season (or wet season) from its long-term average and $\varepsilon_{1,i,j}$ is the random error term. Table 1 gives details on the measurement of these variables.

Table 1 Definition of variables

Variables	Definition	Source of data
Outcome variable		
Commercialization (share of farm output sold)	The gross value of output from sold quantity as a proportion of the gross value of output from harvested quantity	Odisha primary household survey
Key variables of interest		
Crop production diversity (number)	Number of crops grown in 2018–19	Odisha primary household survey
Access to groundwater irrigation (dummy)	1 if the household used privately owned borewells or tube wells, otherwise 0	Odisha primary household survey
Other control variables		
Household characteristics		
Male head (dummy)	1 if the head of the household is a male person, otherwise 0	Odisha primary household survey
Age of head (years)	Age of the household head in years	
Illiterate household head (dummy)	1 if the household head has no formal education, otherwise 0	
Household asset (score)	Score created by summing ownership of 26 consumer assets (housing, vehicles, electronic devices, etc.)	
Livestock ownership (livestock units)	The number of livestock households owns measured in terms of livestock units	
Household size (number)	Number of members living in the household	
Scheduled Caste (dummy)	1 if a household belongs to a scheduled caste (SC)	
Scheduled Tribe (dummy)	1 if a household belongs to a scheduled tribe (ST)	
Other marginalized castes (OBC)	1 if the household belongs to OBC category	
Socially marginalized group (dummy)	1 if a household belongs to a scheduled caste (SC), scheduled tribe (ST), or other marginalized castes (OBC)	
Area of land owned (acres)	Owned land in acres	
Credit (dummy)	1 if the household has taken any credit	
Geographical location		
Distance to the local market (km)	Distance to the closest local market in kilometers	Odisha primary household survey
Distance to Government agriculture markets (km)	Distance to closest Government notified agriculture markets in kilometers	Geo-coordinates from PMGSY rural facilities dataset
Distance to an agricultural collection center (km)	Distance to the closest agricultural collection center in kilometers	
Distance to public transport facility (km)	Distance to closest public transport facility in kilometers	Odisha primary household survey
Distance to block headquarters (km)	Distance to block headquarters in kilometers	Geo-coordinates from PMGSY rural facilities dataset
Distance to nearest waterway (km)	Distance to the closest river, canal, pond, or lake in kilometers was measured by digitizing water bodies in an open street map	Open street maps
Rainfall anomaly		

5.1.2 Identification problem

If in Eq. (1), all factors that influence crop commercialization is controlled for, then there is no correlation between $PIR_{i,j}$ and $\varepsilon_{1,i,j}$. In such a situation an OLS estimator would produce unbiased estimates of β_1. However, $PIR_{i,j}$ is potentially endogenous as there may exist some unobserved factors omitted in the model that affect both the outcome variable and the use of private irrigation systems. For example, unobserved factors such as a farmer's ability, managerial and entrepreneurial skills, or risk-taking capability could simultaneously affect $PIR_{i,j}$ and the outcome

Table 1 (continued)

Variables	Definition	Source of data
Rainfall anomaly index (standardized score)	The rainfall anomaly index is measured as a standardized score of deviation of the previous year's *Kharif* season from historical averages (16 years) within a 5-km radius of the household *Rain anamoly index*$_i = \frac{R_{it-1} - \overline{R}_i}{R_i^{SD}}$, here R_{it-1} indicates the previous year's (2017–18) rainfall during the *Kharif* season within a 5-km radius of the household. $\overline{R}_i$ is the average *Kharif* rainfall within a 5-km radius of the household from 2003 to 2019 and R_i^{SD} is the standard deviation of historic average *Kharif* rainfall within a 5-km radius of the household	CHRS data portal
Instrument		
Water erosion around the neighborhood (share of total area)	Fraction of area affected by water erosion within a 5-km radius of the household	ISRO's Bhuvan geo-portal; Terrestrial science land degradation dataset 2005–06
Mean soil inorganic carbon densities (kg/m^2)	Average soil inorganic carbon content within a 5-km radius of the household (kg/m^2)	ISRO's Bhuvan geo-portal; Terrestrial science Indian soil dataset 2005–06

variable. Furthermore, there could be issues of reverse causality, where households growing more crops feel the need to invest in private groundwater irrigation systems. To address potential concerns regarding endogeneity in Eq. (1), an instrumental variable approach is employed, by implementing the two-staged residual inclusion method. According to this approach, in the first stage, determinants of households using groundwater irrigation are estimated, and then the residuals from the reduced form equation are included as an additional regressor in the second stage regression model of crop commercialization (Wooldridge, 2015). This allows for controlling for possible correlations between unobservable

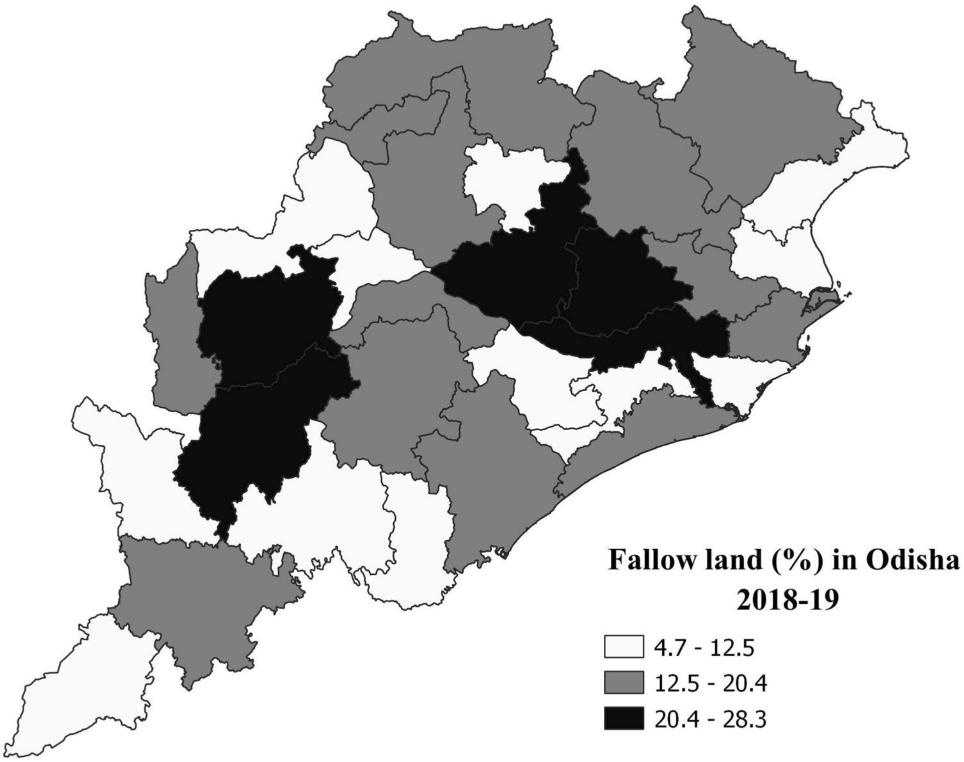
Table 2 Cropping and rainfall pattern in the study region

	(1) Zaid season (March 2018 to May 2018)	(2) Kharif season (June 2018 to September 2018)	(3) Rabi season (October 2018 to February 2019)	(4) Total (March 2018 to February 2019)
Rainfall pattern				
Average rainfall (mm)	182.21	507.77	25.94	715.92
Long run average (mm)	122.23	430.42	36.55	589.25
Seasonal rainfall as a % of total long-run rainfall	21%	73%	6%	
Cropping pattern				
Gross cropped area (GCA, acres)	0.21	1.59	0.47	2.27
Gross irrigated area (acres)	0.20	0.41	0.45	1.06
Overall irrigation ratio (%)	95%	26%	96%	47%
The area under (% of GCA):				
Rice	13%	91%	17%	68%
Vegetables	67%	8%	70%	26%
Others	20%	1%	13%	5%
Marketing pattern				
Percentage of the gross value of harvested quantity sold in the market:				
Rice	87%	30%	6%	12%
Vegetables	91%	83%	89%	88%

1 acre is equal to 0.5 hectares

Source: Household survey and CHRS rainfall data portal

Fig. 2 Fallow land as a percentage of the total geographical area in Odisha



factors that affect groundwater irrigation usage and crop commercialization. The standard errors in Eq. (1) are recalculated by bootstrapping using 10,000 replications. Further, since the dependent variable is a fractional response variable that is bounded between 0 and 1. An OLS specification on a fractional dependent variable could result in predicted values lying outside the unit interval (Wooldridge, 2010). Therefore, a fractional probit specification in a generalized linear model (GLM) is used as an alternative to linear models (Papke & Wooldridge, 1996).

It is usually difficult to find valid instruments that are correlated with access to private groundwater irrigation and uncorrelated with the outcome variable, however, one plausible instrument can be considered to address the issue of endogeneity. In this study, the average fraction of land within a five-kilometer radius of the household affected by water erosion in 2005–06 is used as an instrument to predict the household's access and use of tube wells and bore wells in 2018-19. The data for this variable comes from ISRO's NISCES program. The GPS coordinates of the household are used to link it with the gridded land degradation data. The land degradation dataset provides information about the fraction of land affected by water erosion within a 5 km X 5km grid. The location of the households in the survey region is in the range of 120 m to 15 km from the Budhabalanga river. Flooding and concentrated heavy rainfall during the monsoon period cause severe water and soil erosion in this region. Due to variations in the proximity of the closest rivers, there is a considerable variation in the area within a neighbourhood in the study zone that is affected by water erosion. Private groundwater irrigation systems such as borewells and tube wells extract groundwater by drilling vertical wells into an underground aquifer. Water erosion loosens the soil and increases the risk of sand and other soil particles entering the well. It can also fill up the borewell and jam the motor of the pump. In regions prone to water erosion, an inner casing of high-quality material is usually installed down to the depth at which water is struck. This increases the cost of the installation of tube wells and bore wells. We, therefore, expect that households that have experienced more water erosion around their neighborhood in the past, are less likely to install tube wells and bore wells. Table A1 in the Appendix shows that the instrument is significant and negatively associated with the endogenous variable at a 1 percent level of significance after controlling for all other regressors. Further, Table A1 presents the F statistics for the joint significance of the excluded instruments. Since we reject the null hypothesis at a 1 percent level of significance, it can be concluded that the relevance criterion is satisfied. Moreover, it is known that if the IV is not strongly correlated with the endogenous variable, then the IV estimates will be imprecise and biased. The literature proposes that an instrument is weak if the F-value is lower than the threshold of 10 (Stock & Watson, 2003). Since, the F-value was found to be 58.4, so it can be cautiously concluded that the instrument is not weak. Table A1 also

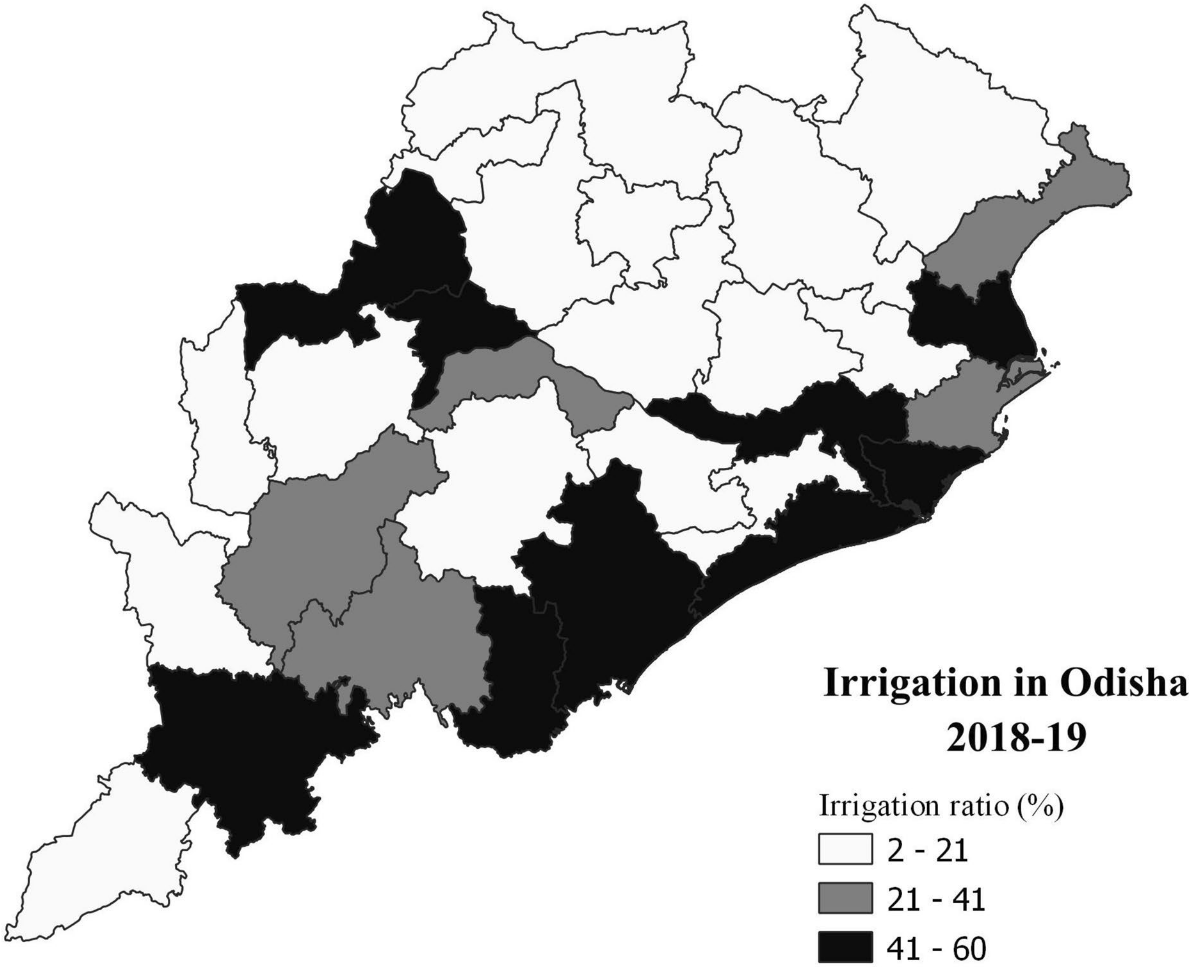


Fig. 3 Gross irrigated area as a percentage of gross cropped area in Odisha

presents the Cragg and Donald minimum eigenvalue statistics and compares them with the largest rejection rate of a nominal 5% Wald test. These results also support the rejection of the null hypothesis of a weak instrument.

The exclusion restriction criteria require that the instrument should not be correlated with the outcome variable except through the endogenous variable. This assumption is not testable. However, it can be argued that the incidence of floods and consequently water and soil erosion is dependent on nature and exogenous to household characteristics. Furthermore, it is unlikely that water erosion in 2005–06 will directly affect crop commercialization in 2018-19 unless past water erosion is correlated with current erosion, which in turn is correlated with what farmers decide to grow on their farms in 2018-19. To test this, Table A2 in the Appendix presents the association between the fraction of land around a neighborhood exposed to water erosion in 2005-06 and the number of crops grown by the farmer in 2018-19 after controlling for other household and geographical factors. The results indicate that past water erosion is not a significant determinant of farmers' current cropping pattern. In addition, a rudimentary test is used to test if the instrument is correlated with the outcome variable by calculating the Pearson correlation coefficient. The results in Table A1 indicate that there is no significant correlation. Finally, a falsification test is used to see whether there is an effect of the instrument on crop commercialization for the sample of households that exclusively used surface irrigation. The exclusion restriction is rejected if the instrument has a statistically significant effect on the outcome (Pizer, 2016). Table A3 in the Online Appendix presents the results of the falsification test. Since area affected by water erosion in 2005-06 does not have a significant effect on crop commercialization levels in 2018-19 for the population using surface irrigation, it can be inferred that the exclusion restriction is not rejected. These tests are reassuring, and therefore it can be assumed that the fraction of land affected by water erosion in the past is a valid instrument in this case. However, it is important to acknowledge that while the estimated models account for many geographical and climate factors that could confound the results, nevertheless, it cannot be ruled out with certainty that unobserved agroecological factors do not correlate with the outcome variable through other indirect mechanisms. Therefore, the findings should not be overinterpreted in the causal sense, rather they should be interpreted as associations between private groundwater irrigation systems and crop commercialization.

5.2 Mechanism of groundwater irrigation and crop commercialization through on-farm production diversity

The second objective of this paper is to test if there is an indirect linkage between crop commercialization and access to groundwater irrigation through on-farm production diversification. To examine this, a system of three structural equations— the crop commercialization equation, the on-farm crop production diversity equation, and the groundwater (tube wells and borewells) irrigation equation— is estimated. The following equations are estimated:

$$COM_{i,j} = \gamma_o + \gamma_1 NCROP_{i,j} + \gamma_3 PIR_{i,j} + \gamma_4' \boldsymbol{H}_{i,j} + \gamma_5' \boldsymbol{G}_{i,j} + \gamma_6 R_{h,j} + \varepsilon_{2,i,j} \tag{2}$$

$$NCROP_{i,j} = \beta_o + \beta_1 PIR_{i,j} + \beta_2' \boldsymbol{H}_{i,j} + \beta_3' \boldsymbol{G}_{i,j} + \beta_4 R_{h,j} + \varepsilon_{3,i,j} \tag{3}$$

$$PIR_{i,j} = \alpha_0 + \alpha_1' \boldsymbol{H}_{i,j} + \alpha_2' \boldsymbol{G}_{i,j} + \alpha_3 R_{h,j} + \varepsilon_{4,i,j} \tag{4}$$

where $\mathrm{COM}_{\mathrm{i,j}}$ measures crop commercialization and $NCROP_{i,j}$ measures crop production diversity, while the other variables are described in Eq. (1). The standard errors in Eq. (2–4) are corrected using a bootstrapping method using 10,000 replications. It is expected that households make simultaneous decisions regarding crop production, marketing, and irrigation, and therefore the error terms are likely to be correlated across equations. Moreover, the explanatory variables, crop production diversity, and groundwater irrigation systems (tube wells and borewells) are within the household's decision set and therefore are likely to be correlated with the error terms due to unobserved household heterogeneity. Therefore, three-staged least square (3SLS) estimation with instruments was used which can account for covariances across equation disturbances. In the crop commercialization equation, there are two potential endogenous variables. Crop production diversity is instrumented by soil fertility as measured by mean inorganic soil carbon density within a 5-km radius of the household and private groundwater irrigation (tube wells and bore wells) with a fraction of the area affected by water erosion within the neighborhood. The two instruments are measured for the year 2005–06.

6 Results and discussion

6.1 Descriptive statistics

Table 3 presents the descriptive statistics of the variables used for our analysis disaggregated by the type of irrigation system. When compared to households that used surface water irrigation systems such as rivers, canals, and ponds, households that used private groundwater irrigation systems such as tube wells and bore wells were wealthier and had significantly more land, consumer assets, and livestock. Furthermore, a larger proportion of socially disadvantaged groups like scheduled tribes (ST), scheduled castes (SC), and other backward castes (OBC) used community irrigation systems. Households that use private irrigation systems are, interestingly, located further from public services and infrastructure, such as transport facilities, block offices, and government-notified farm markets. This could be because households that are distantly located have fewer options for off-farm income and are consequently more reliant on crop production, which could be a key factor in deciding whether to invest in private groundwater irrigation systems. Additionally, it can be observed that, households that depended on community irrigation systems experienced in the past greater water erosion around their neighborhood. This could be because regions that are prone to water erosion have a higher cost of setting up private groundwater irrigation systems and can be prone to damage as discussed in Sect. 5.1. Table 3 also indicate that crop commercialization, and crop production diversity is significantly more for households that used private irrigation systems than for household that used community irrigation systems. Some of these differences in the outcome variables could be due to using tube wells and bore wells, but it could also indicate a systemic difference between the two groups. Therefore, using econometric analysis, the study analyses the association between private groundwater irrigation systems and crop commercialization in Sect. 6.2.

6.2 Regression results

6.2.1 Association between groundwater irrigation and crop commercialization

Table 4 column (1) first shows the results of Eq. (1) without accounting for fractional response outcome variable and endogeneity. The results suggest that access to groundwater irrigation has a positive and significant effect on crop commercialization. These results, however, could be confounded by unobserved factors and therefore the estimates could be biased. Therefore, column (2) presents the results using the instrumental variable control function approach which accounts for endogeneity. Since the outcome variable is fractional, Column (2) estimates the second stage using

Table 3 Descriptive statistics of the variables used in the econometric analysis

	(1)		**(2)**			
	Groundwater irrigation (dummy)		**Other community-based irrigation (dummy)**			
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Difference**	**SE**
Outcome variables						
Crop production diversity (number)	7.29	4.69	5.87	4.22	1.43***	0.31
Commercialization (share of farm output sold)	0.45	0.32	0.33	0.31	0.11***	0.02
Household characteristics						
Male head (dummy)	0.93	0.25	0.92	0.28	0.02	0.02
Age of head (years)	50.57	13.39	50.59	13.64	-0.02	0.92
Illiterate household head (dummy)	0.15	0.36	0.18	0.39	-0.03	0.03
Household asset (score)	10.92	3.13	9.79	3.46	1.14***	0.22
Livestock ownership (livestock units)	1.19	1.00	1.08	0.98	0.11*	0.07
Household size (number)	3.80	1.44	3.54	1.43	0.26***	0.10
Scheduled Caste (dummy)	0.15	0.36	0.21	0.41	-0.05**	0.03
Scheduled Tribe (dummy)	0.13	0.33	0.24	0.43	-0.11***	0.03
Other marginalized Caste (dummy)	0.52	0.50	0.42	0.49	0.104***	0.03
Any socially marginalized group (dummy)	0.80	0.40	0.87	0.34	-0.06**	0.03
Area of land owned (acres)	1.33	1.34	1.07	1.21	0.25***	0.09
Credit (dummy)	0.66	0.48	0.58	0.49	0.08**	0.03
Geographical location						
Distance to a local market (km)	4.92	4.20	4.65	4.00	0.27	0.28
Distance to Government agriculture markets (km)	7.33	3.42	6.48	3.41	0.85***	0.23
Distance to an agricultural collection centre (km)	9.63	4.59	11.50	4.04	-1.87***	0.30
Distance to closest public transport facility (km)	3.16	2.74	1.87	2.07	1.29***	0.17
Distance to block headquarters (km)	10.25	4.07	8.52	4.03	1.73***	0.28
Distance to nearest waterway (km)	4.49	4.06	4.67	4.02	-0.19	0.28
Rainfall anomaly						
Rainfall deviation in last Kharif season[a] (standardized score)	0.73	0.04	0.74	0.04	-0.01**	0.00
Instrument						
Water erosion[b] (share of total area)	0.44	0.16	0.53	0.14	-0.09***	0.01
Mean soil inorganic carbon densities (kg/m^2)	0.72	1.15	0.51	0.79	0.21***	0.07
Observations	608		327		935	

1 acre is equal to 0.5 hectares. Livestock conversion rates: Cattle 0.5; Buffalo 0.5; Sheep/Goat 0.1; Pig 0.2; Poultry 0.01

*Significant at 10% level; ** Significant at 5% level; ***Significant at 1% level

[a] Measured using remotely sensed data by creating a buffer of a 5-km radius of the household

[b] Water erosion and soil carbon content data are taken from ISRO's Bhuvan geo-platform, 2005–06. Details on the measurement of variables are presented in Table 1

a fractional response probit model. For ease of interpretation, we present marginal effects at the means for all variables. Therefore, all coefficients can be interpreted as semi-elasticities. The results of the reduced form equation are presented in Table A1 in the Online Appendix. Since the predicted values of the residuals are used in the second stage, the standard errors of the marginal effects are corrected by a bootstrapping method using 10,000 replications. The IV results are almost identical to the OLS results. The results indicate that private groundwater irrigation systems such as tube wells and borewells increase crop commercialization by 0.06 index points. This is equivalent to a 18% increase in crop commercialization scores relative to the mean commercialization scores of households who used community irrigation systems such as canals and tanks. The results of the second stage IV estimation without accounting for fractional response are shown in Table A4 in the Appendix. The results are like the ones presented in Table 4, which is reassuring.

Table 4 Association between groundwater irrigation systems and crop commercialization

	(1) Crop commercialization (share) OLS	(2) Crop commercialization (share) IV-Fractional probit[a]
Groundwater irrigation (dummy)	0.07***	
	(0.021)	
Groundwater irrigation (dummy)-instrumented		0.06***
		(0.024)
Male head (dummy)	0.04	0.05
	(0.040)	(0.050)
Age of head (years)	-0.00	-0.00
	(0.001)	(0.001)
Illiterate household head (dummy)	0.03	0.03
	(0.031)	(0.035)
Household asset (score)	0.01***	0.01***
	(0.004)	(0.004)
Livestock ownership (livestock units)	0.01	0.01
	(0.010)	(0.011)
Household size (number)	-0.01	-0.01
	(0.007)	(0.008)
Scheduled Caste (dummy)	-0.05	-0.06
	(0.039)	(0.042)
Scheduled Tribe (dummy)	-0.11***	-0.13***
	(0.036)	(0.041)
Other socially marginalized castes (dummy)	-0.04	-0.04
	(0.028)	(0.029)
Area of land owned (acres)	0.08***	0.09***
	(0.018)	(0.020)
Square of land ownership (acres)	-0.01***	-0.01***
	(0.003)	(0.004)
Credit (dummy)	0.01	0.02
	(0.020)	(0.022)
Distance to an agricultural collection centre (km)	-0.01	-0.01
	(0.008)	(0.009)
Distance to block headquarters (km)	0.01	0.01*
	(0.007)	(0.008)
Distance to regional bus stand (km)	0.00	0.00
	(0.007)	(0.008)
Distance to Government agriculture markets (km)	-0.03***	-0.03***
	(0.008)	(0.009)
Distance to the local market (km)	0.02***	0.02***
	(0.003)	(0.003)
Distance to nearest waterway (km)	0.02**	0.02*
	(0.009)	(0.011)
Rainfall deviation in the last Kharif season (standardized score)	0.02	0.06
	(0.893)	(0.944)
Block fixed effects	Yes	Yes
Observations	931	931

Groundwater irrigation is measured as a binary variable that indicates whether a household uses tube wells or borewells. 1 acre is equal to 0.5 hectares. The calculated mean Variance Inflation Factor (VIF) stands at 4.63, suggesting that the presence of multicollinearity is not a cause for concern

Standard errors are presented in parenthesis, and it is bootstrapped with 10,000 replications

*Significant at 10% level; ** Significant at 5% level; ***Significant at 1% level

[a] Marginal effect is reported

Table 5 Mechanism of groundwater irrigation and crop commercialization through production diversity (3SLS estimates)

	(1) Crop commercialization equation	**(2) Crop diversification equation**	**(3) Groundwater irrigation equation**
Groundwater irrigation (dummy)	0.084	3.603**	
	(0.461)	(1.759)	
Crop production diversity (number)	0.430***		
	(0.056)		
Male head (dummy)	0.099	-0.082	0.016
	(0.227)	(0.567)	(0.061)
Age of head (years)	-0.010**	0.020*	-0.001
	(0.005)	(0.011)	(0.001)
Illiterate household head (dummy)	0.197	-0.390	0.011
	(0.159)	(0.398)	(0.046)
Household asset (score)	-0.080***	0.159**	0.012**
	(0.027)	(0.064)	(0.006)
Household size (number)	-0.013	-0.080	0.020*
	(0.048)	(0.119)	(0.010)
Socially marginalized group (dummy)	0.206	-0.384	0.008
	(0.175)	(0.424)	(0.041)
Area of land owned (acres)	-0.346**	0.898***	0.046
	(0.146)	(0.317)	(0.028)
Square of land ownership (acres)	0.042	-0.114*	-0.003
	(0.027)	(0.061)	(0.004)
Distance to the local market (km)	-0.092***	0.258***	-0.004
	(0.022)	(0.042)	(0.004)
Distance to an agricultural collection centre (km)	-0.009		0.002
	(0.021)		(0.014)
Distance to block headquarters (km)	-0.051**		
	(0.024)		
Rainfall deviation in the last Kharif season (standardized score)	-7.552***	8.204	1.394
	(2.549)	(5.353)	(1.963)
Distance to closest public transport facility (km)			0.035***
			(0.011)
Distance to nearest waterway (km)			0.008
			(0.022)
Mean soil inorganic carbon densities (kg/m^2)		-0.282	0.008
		(0.174)	(0.013)
Water erosion (share of total area)			-0.509**
			(0.249)
Block fixed effects	Yes	Yes	Yes
Observations	931	931	931

Groundwater irrigation is measured as a binary variable that indicates whether a household uses tube wells or borewells. 1 acre is equal to 0.5 hectares

Standard errors are presented in parenthesis, and it is bootstrapped with 10,000 replications

*Significant at 10% level; ** Significant at 5% level; ***Significant at 1% level

[a] Marginal effect is reported

In an alternative specification, the effects of variation in the intensity of use of groundwater irrigation is captured by redefining the main independent variable that captures access to groundwater irrigation. Instead of treating groundwater irrigation as a binary variable, it is redefined by combining the irrigation ratio and whether a household exclusively utilized groundwater for irrigation. The results of this alternative specification are outlined in Table A5 in the Online Appendix and the results are somewhat similar to the ones presented in Table 4. The results suggest that all else equal, a one unit increase in groundwater irrigation ratio increases crop commercialization by 0.02 index points. As the measurement of the irrigation ratio could contain inaccuracies, our primary specification draws on the estimates provided in Table 4.

The empirical results presented in this section provide evidence that indicates that utilization of groundwater resources for irrigation fosters conditions that are conducive to increasing market-oriented farming. The inherent reliability of groundwater sources, even during dry spells or seasonal fluctuations in surface water availability, seems to empower farmers to plan their cultivation schedules more effectively. Consequently, this enables them to align their crop production with market demand, leading to higher levels of crop commercialization. On the other hand, the results suggest that surface water irrigation, due to its susceptibility to variations in rainfall and other external factors, might limit farmers' ability to consistently engage in commercial crop production. This could stem from the uncertainty associated with surface water availability, which can impact planting decisions and, subsequently, the degree of crop commercialization. These findings underscore the importance of considering groundwater irrigation methods in strategies aimed at increasing crop commercialization and improving overall agricultural productivity in eastern India where irrigation potential has not been utilized. However, overuse of groundwater poses significant threats to both agricultural and environmental sustainability. Excessive withdrawal of groundwater can lead to depletion of aquifers, land subsidence, and salination in coastal areas. Moreover, in the longer-term, over-exploitation of groundwater resources can have severe consequences on the availability and quality of water for domestic and industrial use. Therefore, it is important that groundwater irrigation interventions are supported with comprehensive monitoring and management systems such that groundwater levels, quality, and extraction rates are tracked at regular intervals. It is also important that policies are enforced to set limits and permits for groundwater extraction. Moreover, investment in artificial recharge methods, like rainwater harvesting and managed aquifer recharge, can replenish groundwater reserves during rainy periods, mitigating the adverse effects of overuse.

Scholars engaged in studying the interconnected relationship between water, food, and energy frequently highlight the importance of treating groundwater and surface water resources as an integrated whole (Mukherji, 2022). However, Indian farmers tend to favor groundwater resources for irrigation not only because of the reliability and control they offer but also due to the inadequacies often associated with surface water irrigation conditions. Surface water sources, such as rivers and canals, can be prone to irregular supply, especially during dry spells or drought periods. Additionally, the infrastructure for surface water distribution might suffer from poor maintenance, leakages, and inefficiencies (Steinhübel et al., 2020). These factors collectively contribute to unpredictable and suboptimal surface water availability for irrigation. Under this circumstance, investments in the modernization of surface irrigation systems can help upgrade canals, pipelines, and distribution networks which could improve efficiency in water delivery and enhance water usage. Furthermore, construction of storage facilities like ponds, tanks, and reservoirs can facilitate capturing rainwater during the monsoon season and using it during the dry season.

6.2.2 Mechanism

The results of the estimation of the system of equations presented in Eqs. (2–5) is presented in Table 5. Column (1) presents the results of the crop commercialization equation, while column (2) and column (3) present the results for the equations on-farm production diversity and groundwater irrigation systems (tube wells and bore wells), respectively. The findings suggest that groundwater irrigation systems have an indirect effect on crop commercialization by boosting on-farm production diversification (column 1). More specifically column (1) shows a positive and significant (at a 1% level of significance) association between on-farm production diversity and crop commercialization, however, the coefficient of groundwater irrigation is not significant. Further, column (2) indicates that access to groundwater irrigation systems increases on-farm production diversity at a 5% level of significance. These findings suggest that groundwater irrigation allows smallholder farmers to diversify their cropping patterns by growing a wider variety of crops, which in turn allows farmers to shift their farming practices towards more market-oriented farming. There could be several reasons for this. First, groundwater irrigation provides a stable water source independent of rainfall fluctuations. This allows farmers to cultivate a wider variety of crops throughout the year, reducing their reliance on seasonal rainfall patterns. Second, groundwater irrigation gives farmers more flexibility in selecting crops based on market demand rather than being constrained by water availability. Third, groundwater sources ensure consistent water supply during dry spells, therefore extending the growing season beyond what is possible with solely rainfed agriculture.

7 Conclusion and policy implications

This study revisits empirically the relationship between groundwater irrigation on crop commercialization. It also analyses the underlying mechanisms of how groundwater affects crop commercialization through on-farm production diversity. Using an instrumental variable approach and a 3SLS simultaneous equation model, the study finds that groundwater is positively associated with crop commercialization in Odisha, an eastern state in India. This effect is indirect, as groundwater irrigation promotes on-farm production diversity, enabling smallholder farmers to change their farming practices towards more market-oriented farming.

The results highlight that assured groundwater irrigation improves farm production diversity as well as crop commercialization. This has important implications for poverty reduction and reducing undernutrition in LMICs. However, as discussed earlier, while groundwater irrigation offers several benefits, it also entails trade-offs that need to be carefully considered. Overuse of groundwater resources can result in the depletion of aquifers, land subsidence, saltwater intrusion, and water contamination. Moreover, reduced groundwater levels can affect ecosystems that rely on groundwater, leading to habitat loss, reduced biodiversity, and even the drying up of streams and rivers (Mukherji & Shah, 2005). Thus, there is a need to find a balanced approach that maximizes benefits while minimizing the negative effects. There are several approaches to finding this middle ground. First, prioritize sustainable groundwater usage by implementing regulations and monitoring systems to prevent over-extraction and aquifer depletion. Second, promoting water-efficient irrigation methods such as drip and sprinkler systems to optimize water use and reduce wastage. Third, adopting an integrated approach that emphasizes the importance of both surface and groundwater resources. This would require investing in modernization of surface irrigation systems to improve efficiency in water delivery and improving reliability of water availability and implementing aquifer recharge methods. Fourth, designing pricing mechanisms that reflect the true value of groundwater and providing incentives for adopting sustainable irrigation methods.

To conclude, this paper has a few limitations worth noting. Firstly, the study utilizes observational data which makes it difficult to establish causality. Although the study employs an instrumental variable approach to address the issue of endogeneity, it cannot entirely exclude the possibility of unobserved agroecological factors influencing the outcome variable through other indirect mechanisms. Therefore, further research with experimental methods and panel data is required to improve the identification strategy. Secondly, the findings of the study are based on a sample of households in eastern India cannot be generalized to other regions. Additional research is needed to increase external validity in different geographic contexts. Thirdly, the study did not observe any instances of households purchasing water from other tube wells or borewell owners in the sample of vegetable growers. However, informal groundwater markets are prevalent in India, and well ownership could have more extensive network effects than this study can account for. Future research should aim to explore the larger network effects of informal groundwater markets.

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Data availability Data will be made available on request.

Declarations

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