The evolution of groundwater governance: productivity, equity and changes in the level of China's aquifers

J. Wang[1,*], J. Huang[1], Q. Huang[2], S. Rozelle[3] & H.F. Farnsworth[3,4]

[1]Center for Chinese Agricultural Policy (CCAP), Institute of Geographical Sciences and Natural Resource Research, Chinese Academy of Sciences, Jia, No. 11, Datun Road, Anwai, Beijing 100101, China
[2]Department of Applied Economics, University of Minnesota, MN 55108, USA
[3]Food Security and Environmental Program, Freeman Spogli Institute for International Studies, Stanford University, Stanford, CA 94305, USA
[4]Department of Economics, University of Waikato, Hamilton, New Zealand
*Corresponding author (e-mail: jxwang.ccap@igsnrr.ac.cn)

Abstract: The overall goal of our paper is to examine how the evolution of groundwater governance in North China has affected the rural economy. Based on a random sample of 48 villages in nine counties in North China, our results show that over the last 15–20 years collectively owned tubewells have been gradually privatized. Our analyses demonstrate that increasing groundwater scarcity and policy intervention (mainly fiscal and financial subsidies for tubewell investment) have led to the observed shifts in tubewell ownership patterns. Our results also show that the privatization of tubewells has affected cropping patterns in North China. When villages shift towards private tubewells, farmers move into more water-sensitive and high-valued crops. Privatization, although having no effect on crop productivity in our sample, has a positive effect on income. Increased groundwater use is also shown to improve income distribution. However, the evolution of tubewell ownership in our study villages comes at a cost: increasing privatization is associated with falling water tables.

As one of the main economic and political centres of China, the population and economy of the Hai River Basin (HRB) and the Lower Reaches of the Yellow River Basin (LRYRB) in North China have grown rapidly over time. (The HRB and the LRYRB cover the municipalities of Beijing and Tianjin, all of Hebei and much of Henan and Shandong provinces.) Since the 1950s the gross domestic product (GDP) of the two regions has increased by a factor of nearly 40 (China National Bureau of Statistics 2002). Both rural and urban areas have contributed importantly to the growth: agricultural GDP has risen by a factor of nearly eight, whereas at the same time, industrial GDP grew by a factor of more than 50. Agricultural yields of wheat and maize rose by between 15 and almost 30% during the 1990s. Agricultural output grew by 20–35%. Facing rising demand for cash crops from domestic and export markets, farmers also began to shift from staples into cash crops, even though such crops often require more intensive use of water and more precise water applications. The development of the regions also made a positive impact on poverty: the poverty rate measures from Hebei and Henan provinces fell from 30% in 1985 to less than 9% in 2001 (Wang 2007).

There are probably many reasons behind such agricultural and industrial growth and associated poverty reduction, yet there has been little empirical analysis of the specific drivers of change. In particular, little research has been done on the impact of the most notable development during the past 20 years: the emergence of China's groundwater economy. Since the late 1960s, surface water availability in the HRB and LRYRB has fallen. During the 1990s, almost no water from the HRB was discharged into the sea; the HRB changed from an open basin to a closed one. From the early 1970s to the late 1990s, water in the Yellow River did not reach the sea for extended periods in many years. Observers have witnessed a steady fall of cultivated area serviced by surface water.

Faced with increasing demands and limited surface water supplies, farming communities in North China began to turn to groundwater in the late 1960s. (The groundwater of the North China Plain mainly exists in a Quaternary aquifer system. About 62% of North China's groundwater resources are stored in the region, which is dominated by piedmont alluvial plains (Hong *et al.* 2008). This system of groundwater aquifers is large: according to the Ministry of Water Resources (unpubl. data), in total, North China has 246 billion cubic metres of groundwater resources and each year users extract about 80 billion cubic metres (of which, much can be recharged). A large share of North China's groundwater is found in aquifers that can be categorized into one of four water-bearing formations (Zhang 2005). Most categorization schemes begin with shallow aquifers and proceed to deep aquifers, describing them by their hydrological characteristics and the average levels of compaction. The first aquifer system is referred to as shallow groundwater aquifers; the second, third and fourth aquifer systems are called deep groundwater aquifers. The average depth of the shallow groundwater aquifers is around 40–60 m. The shallow groundwater aquifer is by far the most used. Many of the shallow aquifers are rechargeable. In contrast, the depth of the deeper aquifers ranges from 120 to 550 m (and more). Although, in general, the levels of compaction of the deep aquifers are higher, many of these aquifers cannot be recharged.) Under the directive of the Central Government, tubewells developed quickly in China during recent decades. By 2005, producers were extracting groundwater from more than 3.5 million tubewells and irrigated nearly 15 million hectares, mainly in the HRB and LRYRB (Ministry of Water Resources 2006). According to a sample of counties surveyed by the authors in 2004, the expansion of tubewells accelerated in the late 1990s. In 2005, nearly 70% of the HRB's water supply came from groundwater (Ministry of Water Resources 2006).

Unfortunately, the expansion of the groundwater economy is not without cost. Rising groundwater extractions have led to falling water tables. For example, in Feixiang County, which is located in the upstream part of the Fuyang River basin (part of the HRB), the shallow water table fell by 0.6 m per year in the 1980s and 1.3 m per year in the 1990s. Even greater rates of decline of the shallow water table occurred in the downstream parts of the basin. Excessive water withdrawals and falling water tables have caused land subsidence in some rural areas, cones of depression under some cities and deteriorating water quality near the coast (Hebei Hydrological Bureau and Water Environmental Monitoring Center 1999).

During this time, although leaving less of an imprint on the landscape, the ownership of tubewells and pumps was also undergoing a fundamental shift, from collective to private. In the 1970s, virtually all wells and pumps belonged to the collective. Although official data are scarce, two sets of data collected by the authors in 2001 and 2004 and described in this paper indicate that private individuals have installed a large majority of new tubewells since the early 1990s (Wang *et al.* 2007). We also found that individuals purchased 80% of new pumps during the 1990s. Surprisingly, despite the scope of the changes in the use of groundwater in general, and the emergence of a private well- and pump-owning sector in particular, there has been almost no research on the impact that these trends have had on regional productivity. Even less is known about how the emergence of a largely private groundwater economy has affected income distribution.

Interestingly, although rising groundwater abstraction (from whatever source) is almost certainly behind the fall in the water table, there is less certainty over the effects of tubewell privatization. (According to China's Water Law (issued in 1988 and revised in 2002), the ownership of water resources (both surface and groundwater resources) lies with the State: according to China's formal water legislation, it is the State Council, on behalf of the State, that exercises the right of ownership of water resources. Under the framework of this law (and other relevant regulations on water management), if individual agents (such as farmers) or organizations (e.g. enterprises) would like to extract any water from China's ground or surface water resource, they need to apply for permission from the local water resource bureau. In other words, according to the law, this means that farmers have the right to sink tubewells if they obtain permission from the local water agency. It should be noted, however, that in many cases it is difficult to implement China's water laws and regulations as written. In fact, Wang *et al.* (2007) showed that the implementation of these regulations has largely not been effective in many regions. For example, based on field surveys, farmers seldom apply for permission to sink their tubewells; requirements on spacing also are often not enforced.) Economic theory suggests that when many individuals pump without regulation from a common aquifer, water will be over-extracted. Some observers have placed blame on private well owners for the fall in North China's water table (Chen & Liu 2008; Wang 2008). (According to the theory of common pool resources (Ostrom, 1990; Bromley, 1992), if agents in a community have free access to a resource, such a resource can be called a common pool resource (or common property resource). For a number of reasons, common pool resources are likely to be overused. The main problem is that because there are no clear property rights (and if there is no exclusion), each agent will extract the resource at a rate that will maximize their current profits without considering the externalities that they are imposing on either other users or on users in the future. In the absence of any effective regulation (or coordination), because all agents that use the common property resource will act similarly, there are typically large negative externalities and the drawdown of the resource is accelerated. Groundwater is one type of common pool resource (Brozović *et al.* 2006). Although the ownership of groundwater belongs to the State, in fact, in most villages in China, farmers can sink tubewells when and where they want without seeking approval (Wang *et al.* 2007). There are few controls on the quantity of pumping. In such physical and managerial environments, farmers should be expected to act in a way that could lead to the 'tragedy of the commons'. Each farmer will consider only the profitability of pumping water for this season and will not consider the consequence of their actions on the level of the resource in the future (or on the profitability of others).) Others (Kendy *et al.* 2004; Wang *et al.* 2005) have suggested that there is no evidence that changes in well governance have accelerated the fall of the water table.

The overall goal of our paper is to examine how the evolution of groundwater governance in North China has affected the rural economy. To address this goal, we have four objectives. First, we want to describe the evolution of tubewell ownership. Second, we examine the nature of the villages and households that have seen

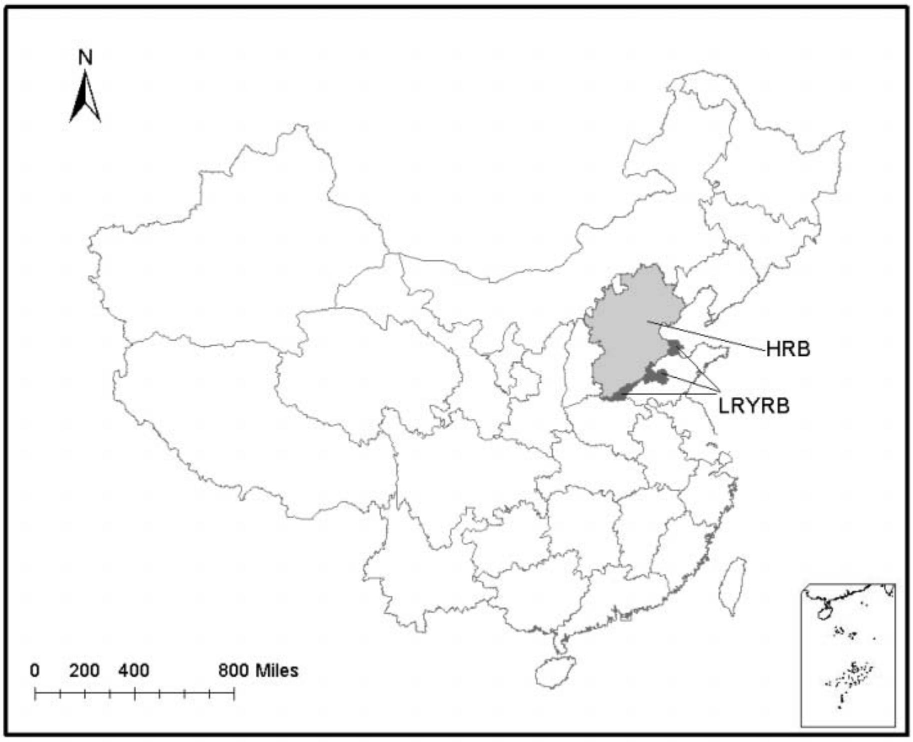

Fig. 1. Location of Hai River Basin (HRB) and the Lower Reaches of the Yellow River Basin (LRYRB) in North China.

their tubewells privatized and measure the factors that influence privatization. Third, we explore the impact of tubewell ownership change on agricultural production, income and the water table. Finally, we also are concerned about the possible negative consequences of the groundwater economy on the distribution of income.

Data

The data for the study come from a survey that the authors conducted in 48 villages in the HRB and the LRYRB in North China (Fig. 1). Although these river basins cover counties in other provinces, our study examines communities in two provinces only, Hebei and Henan Provinces. To be representative, the sample villages were randomly selected. All villages in the sample kept detailed accounting records on community-level socio-economic and water issues. Detailed interviews with village leaders and others who had been village residents for the entire sample period were also conducted. The field survey of 48 villages covers four periods: 1990, 1995, 2001 and 2004.

During the survey, enumerators identified two types of tubewell governance: collective and private. If the village's leadership council owns the tubewell, we define it as collective; otherwise the tubewell is defined as private. There are two types of private tubewells. If a tubewell belongs to a single individual or family, we call it an individual tubewell. Other private tubewells are owned by groups of individuals. Because, in many of the groups, the members are assigned shares that indicate the investment stake that each member has in the tubewell, the groups are often called shareholding groups and their tubewells are called shareholding tubewells. In executing our village questionnaire, enumerators asked village leaders to recall the total number of operating tubewells by ownership type in each of the survey's four target years.

The survey also collected information that we use to understand the determinants of tubewell ownership and several measures of the effects of ownership shifts on crop production, income and water resources. The determinants of tubewell ownership include the scarcity of water and the per capita income level of the village. Groundwater scarcity is defined as the depth of the water table in a tubewell after at least 3 months of non-use (typically in the autumn). We asked village leaders whether the government provided either fiscal subsidies or bank loans for aiding the collective or individuals to invest in tubewells. We also recorded cropping patterns (the share of overall sown area accounted for by each crop) and crop yields to account for productivity impacts. In addition, we collected information on per capita farmer income to explore the relationship between income and changing patterns of well ownership. Finally, as control variables, we collected information on other factors, including per capita land area, the share of surface irrigation, water quality, the share of the village labour force with higher than primary-level schooling, the share of the non-agricultural labour force, distance to roads and the number of firms in the village.

Fig. 2. Shifts in tubewell ownership in Hebei and Henan Provinces, 1990–2004.

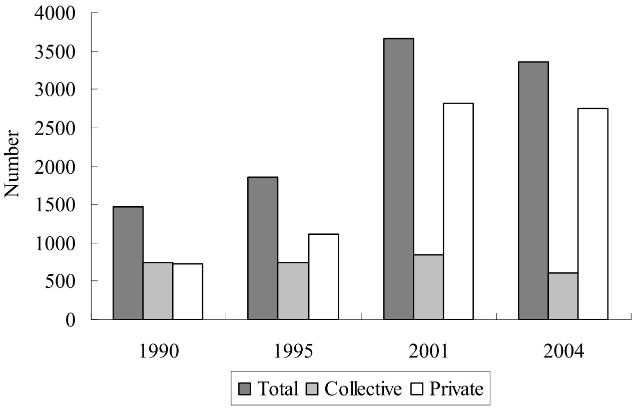

Fig. 3. Change of tubewell numbers, 1990–2004.

The evolution of tubewell ownership

Tubewell ownership in our study area shifted sharply from collective to private over the study period (Fig. 2). In 1990 collective ownership accounted for 51% of all tubewells. From 1990 to 2004, however, the collective ownership of tubewells diminished whereas the share of private tubewells increased from 49 to 81%. Although the shift of tubewell ownership occurs throughout our entire sample, its pattern varies across the study counties and between villages within the counties.

The shift of tubewell ownership has come mostly from the establishment of new tubewells rather than a change in ownership of existing ones (Fig. 3). As a result of the fall of the water table during the 1990s (and the lack of maintenance of pumps and engines), a number of collective tubewells have became inoperable over the past two decades. In fact, the absolute number of collective tubewells fell between 1990 and 2004 (Fig. 3). During this time, the number of private wells increased rapidly.

Although the number and proportion of private tubewells increased over the entire study period, as for collective wells, numbers declined between 2001 and 2004 (Fig. 3). Although it is beyond the scope of this study to identify reasons for this, one explanation is that the falling water table has affected the groundwater economy. As groundwater levels have fallen, many tubewell operators may have abandoned their wells, and some may not have been replaced.

Tubewell ownership, resource scarcity and policy intervention

Researchers in recent years have analysed the determinants of institutional innovation both theoretically and empirically. For example, White (1995) found that government policies, the degree of democratization and financial market liberalization play important roles in institutional change. Otsuka (1995) showed that in much of the empirical literature, environmental and population factors, government policies and other socio-economic variables are the main determinants of institutional change. Uphoff (1986) and Tang (1991) identified three kinds of factors affecting water management organizations in particular: the physical and technical characteristics of the resource; the characteristics of the group of users; and the nature of institutional arrangements.

Although little empirical work has focused specifically on groundwater governance, the international literature has identified several factors that affect tubewell ownership. Based on a case study of tubewell ownership innovation in Pakistan, Meinzen-Dick (1996) concluded that the emergence of private tubewells is mainly due to the changes of groundwater and surface water utilization, farm scale and population intensity. Shah (1993) showed how the emergence of institutions that encourage water sales in villages has levered the rise in private tubewell ownership. Barker & Molle (2005) pointed to the increased availability of reliable pumping technology and hinted that this has been a factor in increasing the rise of private tubewell ownership in South and SE Asia. Despite the importance of groundwater in China's agriculture and its rapid evolution over time, almost no work has attempted to analyse the factors that have affected ownership decisions in China.

Drawing on descriptive analysis based on the data from Hebei and Henan, we find that several factors are found to be associated with the shift in tubewell ownership from collective to private. Most strikingly, factor endowments, especially water, are correlated with ownership changes (Table 1). Specifically, in villages in which water is scarce, tubewell ownership has evolved quickly. Although the patterns in the descriptive statistics do not prove causality, they are consistent with the idea that private tubewells may have emerged in response to North China's growing groundwater scarcity.

Government programmes to encourage investment by farmers and village leaders may also have influenced

Table 1. *Relationship between tubewell ownership and resource endowment and policy measures in Hebei and Henan Province, 1990–2004*

	Year/share of private tubewells (%)			
	1990/49	1995/60	2001/78	2004/81
Water scarcity				
Water table (m)	9	11	14	20
Policy intervention				
Villages receiving investment subsidies for water projects (%)	2	9	23	12
Villages receiving bank loans for water projects (%)	0	2	14	7
Village fiscal health				
Per capita village real fiscal income (yuan)	27	28	28	15

Table 2. *Relationship between tubewell ownership and cropping patterns and yields in Hebei and Henan Province, 1990–2004*

	Year/share of private tubewells (%)			
	1990/49	1995/60	2001/78	2004/81
Share of sown areas (%)				
Wheat	44	45	45	41
Maize	27	26	26	30
Cotton	6	6	9	10
Other cash crops	5	6	6	10
Crop yield (kg ha^{-1})				
Wheat	4155	4515	4890	5295
Maize	4650	5010	5625	5490
*Real annual farm income (yuan)**	815	1211	1831	2261

* 1990 prices.

the pattern of tubewell ownership. Officials have implemented two main policies (fiscal subsidies and loans) that affect tubewell ownership decisions. Not all actors in any given community, however, are eligible for these programmes. Whereas subsidy programmes mainly support the investment efforts of single farmers, banks typically target special loans to village leaders. Because of the targeting rules of the two policies, we expect that in areas that have had relatively large fiscal subsidy programmes, there should have been more of a shift towards private ownership. Likewise, in those areas with an active bank loan programme, access to special investment funds by the village leadership council may be keeping the collective active in maintaining or expanding their tubewells. Our descriptive data provide support (although not proof) for the hypothesis that the tubewell economy is dependent, at least in part, on government support (Table 1).

Tubewell ownership, production and income

Descriptive statistics from the data not only suggest that certain factors have systematically induced the rise of private tubewell ownership, but also indicate that changes in tubewell ownership have led to shifting cropping patterns (Table 2). Although there certainly are many other factors that affect cropping patterns, our data show that when the share of private tubewells increased from 49 to 81% between 1990 and 2004, the share of sown area under wheat cultivation decreased by 3% (Table 2). At the same time, the share of areas under maize and cotton increased (Table 2). Most importantly, the area devoted to other crops (mostly horticulture crops) rose by 40% (from 6 to 10 percentage points; Table 2).

Although the data show a fairly strong relationship between tubewell ownership and cropping patterns, the relationship between ownership and yields is less clear. It is true that the descriptive data indicate that yields increase over time as private tubewell ownership increases (Table 2). There are, of course, many reasons (e.g. new technology) why yields may have risen. The correlation between tubewell ownership and rates of yield increase is less clear; yields rise less rapidly than increases in private tubewell ownership.

Descriptive statistics also indicate that as the percentage of private tubewells increases, farmers' earnings also increase (Table 2). When the share of private tubewells increased from 49 to 81% between 1990 and 2004, annual real farmer income also increased from 815 to 2261 yuan. However, a number of other factors also may be contributing to the observed income increases, and so before drawing any conclusions, multivariate analysis is needed.

Determinants of tubewell ownership and impact analysis

Based on the above discussion and following the literature (e.g. Fujiie *et al.* 2006), we propose the following econometric model to analyse the determinants of tubewell ownership:

$$M_{jt} = \alpha + \beta W_{jt} + \gamma P_{jt} + \phi Z_{jt} + Dv_j + \varepsilon_{jt}. \quad (1)$$

In equation (1), M_{jt} represents the share of private tubewells in village j in year t. The variables on the right-hand side of equation (1) are those that explain differences in tubewell ownership decisions among villages and over time. The variable W_{jt} represents the degree of groundwater scarcity, measured as the level of the water table. We include a set of policy variables (policy interventions), P_{jt}, to assess the effects of policy on tubewell ownership patterns. Because we also use P_{jt} as instruments to identify tubewell ownership in the performance equations (see equation (3) below), a fuller discussion follows below.

In explaining tubewell ownership, a number other factors are also controlled; for example, the degree of land scarcity measured as arable land per capita, and the village's ability to draw on its fiscal resources for investment measured as per capita village fiscal income. The rest of the control variables include the share of surface water irrigation, groundwater quality (1 = good and 0 = bad), the share of the labour force with a higher than primary school education, and the share of the non-agricultural labour force. Finally, we also use a village (Dv_j) dummy variable to control for unobserved village effects. The symbols α, β, γ, δ, ϕ and η are parameters to be estimated and ε_{jt} is the error term.

Tubewell ownership may be endogenous in the impact analysis, as in the second part of this paper, in which multivariate analysis is used to measure the effect of tubewell ownership on sown area decisions, yields and income. Therefore, variables that will be able to identify the effect of tubewell ownership on agriculture decisions need to be included. To do so, in equation (1) the vector P_{jt}, which is made up of the two policy intervention variables, is introduced. The first variable equals unity if the village received financial subsidies for investing in tubewells from county officials in the water bureau, and zero if not. The second policy variable equals one if the village received targeted bank loans for tubewell investment, and zero otherwise. The authors believe that the formulaic way in which upper-level officials allocate the grants and loans allows us to use these policy variables as instruments. In other words, officials used a predetermined formula as a basis on which they distributed the investment funds and loans. Assuming this is so, investment grants and targeted bank loans should have been expected to affect tubewell ownership, but will have had no independent effect on sown area decisions or yields.

The possible effects of tubewell privatization on the water table are also of interested. To do so, the following equation is introduced:

$$W_{jt} = \alpha + \beta M_{jt} + \gamma N_{jt} + \partial IV_{jt} + \phi Z'_{jt} + Dv_j + \varepsilon_{jt}. \quad (2)$$

In equation (2) the water table, W_{jt}, is specified as a function of tubewell ownership, M_{jt}, an interaction variable, N_{jt} (tubewell ownership multiplied by the 2004 year dummy), a single instrumental variable, IV, other control variables, Z'_{jt} and village dummy variables (Dv_j). Besides being needed for our econometric estimation, the results of equation (2) should be of interest to policy makers, as they will be useful in assessing whether or not tubewell ownership reform accelerates the drawdown of water tables. The level of the water table in 1990 is used as the instrumental variable in equation (2). It is assumed that the instrumental variable can at least in part explain the level of the water table during the study period but has no direct or independent influence on tubewell ownership (except through its effect on groundwater scarcity).

To analyse the impact of tubewell ownership on cropping patterns and income, the following equation is introduced:

$$y_{jt} = \alpha + \beta \widehat{M}_{jt} + \gamma \widehat{W}_{jt} + \delta N_{jt} + \phi Z''_{jt} + Dv_i + \varepsilon_{jt} \quad (3)$$

where y_{jt} measures two types of performance indicators: either the share of crop area sown to one of the region's major crops (wheat, maize, cotton and other cash crops) or real annual farmer income (in 1990 prices). The variables on the right side of equation (3) are those that explain the performance indicators. Using the identification strategy discussed above, we include the prediction of the tubewell ownership variable ($\widehat{M}_{jt}$) from equation (1) and the prediction of water table ($\widehat{W}_{jt}$) from equation (2). The interaction variable, N_{jt}, which is the same as that in equation (2), is included. We also include Z''_{jt} to control for other factors that might affect cropping patterns and income. In addition to the control variables in equation (1), Z'' also includes measures of water quality.

To analyse the impact of tubewell ownership on yields, the following equation is introduced:

$$y_{jt} = \alpha + \beta \widehat{M}_{jt} + \gamma \widehat{W}_{jt} + \delta N_{jt} + \phi Z''_{jt} + Dv_i + Dy_t + D\varepsilon_{jt} \quad (4)$$

where y_{jt} measures the yields of major food grain crops (wheat and maize). Except for the dummy year (Dy_t), the variables on the right side of equation (4) are the same as those in equation (3). The dummy year is to control the impact of technological progress on yields.

Determinants of tubewell ownership and its impact on the water table

The econometric estimation of the two-stage least-squares (2SLS) model performs well for the determinants of tubewell ownership equations (Table 3, column 1). The 'goodness of fit' measure, adjusted R^2, of 0.67 is sufficiently high for this type of analysis. Most of the coefficients of control variables also have the expected signs and a number of the coefficients are statistically significant. For example, the coefficient of the variable measuring the village's fiscal income level is negative and significant (Table 3, row 10). The coefficient of the share of the non-agricultural labour force is significant and positive (Table 3, row 12).

More importantly, when examining the variables of interest, the results show that increasing groundwater scarcity affects the evolution of tubewell ownership. The coefficient on the water table level variable is positive and significant. All other things being held constant, when the water table falls and water becomes scarce, tubewell ownership shifts from collective to private. (Although our analysis (which seeks to use methods that allow us to identify causality) clearly shows that the decline in the water table was one factor that triggered privatization, it is certainly possible that in other places the sequence is: deregulation leads to privatization, which leads to increases in extraction, which leads to falling levels of groundwater, which finally leads to water scarcity. We would like to thank an anonymous reviewer for this comment.) Our findings can be interpreted as support for the induced innovation hypothesis, a hypothesis that has been found to be true in many studies in disciplines other than water management. Changes of natural resource endowments will induce institutional innovation.

Although the robustness of the coefficients on the groundwater scarcity variable in the tubewell ownership equation suggests that endogeneity may not be a major statistical problem, examining the groundwater scarcity equation demonstrates the statistical validity of our instrumentation strategy (Table 3, column 2). The depth of the water table in 1990 is a strong indicator for the depth of the water table in later years. In addition, the χ^2 test used in the second part of the exclusion restriction test shows that the instrument variables have no independent explanatory in the tubewell ownership equation. In other words, the Hausman–Wu exclusion restriction test demonstrates that our instrument is valid. (To test if the set of identifying instruments are exogenous, a Lagrange multiplier test can be used (Hausman–Wu exclusion restriction test). This test is divided into four steps: step 1, run equation (2) and save the predicted water table levels; step 2, run equation (1) where water table is the predicted value from step 1, and save the residuals; step 3, regress residuals from equation (1) on the instrumental variable (the level of the water table in 1990); step 4, calculate the test statistic, $N \times R^2$, where N is the number of observations, and R^2 is the measure of goodness-of-fit in the third step regression. It shows a χ^2 distribution. In our study, the test statistic is 0.001 and we cannot reject the null hypothesis that there is no correlation between the exogenous instruments and the disturbance term from tubewell ownership equation (1). This means that we have a set of instruments that are statistically valid.)

The coefficient of the tubewell ownership variable in the groundwater scarcity equation is also of interest in its own right (Table 3, column 2, row 1). Our results suggest that the water table is lower in villages with more private tubewell ownership. In other words, the finding indicates that the shift to private ownership does lead to a more rapid fall in the water table than in those villages that have collective tubewell ownership. (In North China, the decline of the water table has occurred before the 1980s. However, the shift in tubewell ownership from collective to private mainly emerged since the early 1980s. Therefore, it is the decline of the water table that first induces the privatization of tubewell ownership. In the latter, the privatization of tubewell ownership has resulted in the decline of the water table.)

In addition to pressures provided by scarce resource endowments, the government's policies also have influenced tubewell ownership, although different programmes have had different impacts (Table 3). The coefficient of the fiscal subsidy variable is positive and significant, suggesting that fiscal subsidies for tubewell investment have promoted the ownership of tubewells by private individuals. In contrast, the coefficient of bank loans is negative (Table 3, column 1, rows 5 and 6), indicating that targeted loans from banks have encouraged the expansion of collective ownership. Both of these shifts are as expected.

Ownership impacts on sown area decisions, yields and income

The results also show that the evolution of tubewell ownership has led to systematic adjustments in the cropping patterns of our sample farmers in the North China Plain (Table 3, column 3–6). The coefficients of the tubewell ownership variable (the share of private tubewells or intercrossing variables multiplied by ownership and the dummy year) in maize, cotton and other cash crop equations are positive and significant (Table 3, columns 4–6, rows 1 and 2). In contrast, the coefficient is negative and significant in the wheat equation (Table 3, column 3). In other words, when the share of private tubewells in a village rises, farmers in our sample shift sown area from wheat and other grain crops to maize, cotton and other cash crops (mainly horticultural crops). Given the greater demand by horticultural producers for timely water deliveries, our results from the sown area equations might be interpreted as meaning that the shift

Table 3. *Regression analysis using two-stage least-squares of the determinants of tubewell ownership and its impact on cropping pattern and yield*

	Row number	(1) Dependent variable (stage 1): share of private tubewells	(2) Dependent variable (stage 2): log of water table	Dependent variable (stage 2): share of sown area				Dependent variable (stage 2) Crop yield per hectare		(9) Dependent variable (stage 2): per capita income
				(3) Wheat	(4) Maize	(5) Cotton	(6) Other cash crops	(7) Wheat	(8) Maize	
Tubewell ownership										
Share of private tubewells (predicted from column 1)	1		0.024	−3.008	2.780	−3.315	1.937	182.077	−7.136	81.232
			(7.19)***	(2.23)**	(1.83)*	(1.96)**	(1.09)	(1.05)	(0.03)	(0.50)
Share of private tubewells × year dummy in 2004	2		0.001	−0.057	0.023	0.101	0.059	−2.365	6.924	6.807
			(0.79)	(3.05)***	(1.07)	(4.27)***	(2.39)***	(0.61)**	(1.29)	(2.98)***
Water scarcity										
Log of water table (predicted from column 2)	3	14.093		118.850	−108.415	123.674	−70.312	−6794.028	1550.184	−2336.079
		(3.48)***		(2.00)**	(1.82)*	(1.86)*	(1.01)	(0.99)	(0.17)	(0.36)
Log of water table in 1990	4		0.517							
			(4.39)***							
Policy interventions										
Dummy of fiscal subsidies for tubewell investment	5	13.117								
		(1.72)*								
Dummy of bank loans for tubewell investment	6	−4.493								
		(0.48)								
Other control variables										
Per capita village fiscal income	7	−0.269		0.034	−0.057	0.080	0.063	11.481	10.595	7.060
		(1.82)*		(0.83)	(1.24)	(1.56)	(1.17)	(2.00)**	(1.28)	(1.43)
Per capita land area	8	−281.979		31.217	75.267	24.440	160.210	4928.073	27762.01	11752.12
		(1.61)		(0.73)	(1.56)	(0.46)	(2.85)***	(0.87)***	(2.60)***	(2.26)**

	Row number	(1) Dependent variable (stage 1): share of private tube-wells	(2) Dependent variable (stage 2): log of water table	Dependent variable (stage 2): share of sown area				Dependent variable (stage 2) Crop yield per hectare		(9) Dependent variable (stage 2): per capita income
				(3) Wheat	(4) Maize	(5) Cotton	(6) Other cash crops	(7) Wheat	(8) Maize	
Share of surface water irrigation	9	0.089	−0.001	0.080	−0.225	0.112	0.015	−9.399	1.731	−6.653
		(0.81)	(0.37)	(1.31)	(3.27)**	(1.47)	(0.19)	(1.20)	(0.17)	(0.90)
Water quality	10		−0.092	4.302	−7.429	12.468	−5.642	−297.785	75.869	−182.402
(1 = good; 0 = bad)			(0.70)	(1.35)	(2.07)	(3.12)***	(1.35)	(0.73)	(0.14)	(0.47)
Share of labour force with higher than primary schooling	11	0.147	−0.012	1.398	−1.272	1.467	−0.725	−83.458	23.718	−12.220
		(0.77)	(3.51)***	(2.27)**	(1.83)*	(1.90)**	(0.89)	(1.04)	(0.22)	(0.16)
Share of non-agricultural labour force	12	0.054		−0.000	−0.013	0.037	−0.007	1.346	−0.379	0.092
		(3.23)***		(0.01)	(2.23)**	(5.80)***	(1.06)	(2.09)**	(0.40)	(0.15)
Distance to road	13	0.269	−0.027	3.484	−3.429	3.504	−2.065	−225.672	161.478	−104.482
		(0.22)	(1.20)	(2.13)**	(1.87)*	(1.71)*	(0.96)	(1.08)	(0.58)	(0.53)
Number of firms	14		−0.002							
			(0.25)							
Constant	15	23.610	0.743	−66.141	143.770	−138.699	47.889	10546.81	−825.111	692.437
		(0.85)	(2.36)***	(1.20)	(2.32)**	(2.00)**	(0.66)	(1.48)	(0.09)	0.10
Observations	16	158	158	158	158	158	158	158	138	158
Adjusted R^2	17	0.67	0.78	0.65	0.87	0.73	0.49	0.70	0.61	0.68

Village dummies and year dummies were included, but are not reported to save space.
* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.
Absolute value of z statistics is given in parentheses.

Table 4. *Number of households by type*

		Total number	Household that used only surface water	Households that used only groundwater	Households that only irrigated conjunctively	Households that do not irrigate	Other households
1	China	1101	612	200	15	258	16
2			(55.59)	(18.17)	(1.36)	(23.43)	(1.45)
3	Hebei	190	1	142	0	46	1
4			(0.53)	(74.74)	(0.00)	(24.21)	(0.53)
5	Liaoning	186	73	21	2	88	2
6			(39.25)	(11.29)	(1.08)	(47.31)	(1.08)
7	Shanxi	194	71	33	2	82	6
8			(36.60)	(17.01)	(1.03)	(42.27)	(3.09)
9	Sichuan	186	162	3	4	16	1
10			(87.10)	(1.61)	(2.15)	(8.60)	(0.54)
11	Zhejiang	171	153	1	7	6	4
12			(89.47)	(0.58)	(4.09)	(3.51)	(2.34)
13	Hubei	174	152	0	0	20	2
14			(87.36)	(0.00)	(0.00)	(11.49)	(1.15)

The total number of households is fewer than 1199, as information on irrigation is missing for some households. The proportion of each type of household is reported in parentheses.

to private tubewell ownership has facilitated the expansion of high-valued crops that have special water needs. In addition, faced with increasing groundwater scarcity, farmers have begun to shift out of water-intensive crops (such as wheat, which requires up to five irrigations per year) to less water-intensive but relatively high-valued crops (such as maize and cotton, which use one to three irrigations per year). Our results indicate that with change of tubewell ownership from collective to private, farmers possibly attach more importance to increasing the value of water use.

In contrast, the results presented here show that there is no significant relationship between tubewell ownership and crop yields (Table 3, columns 7 and 8). The coefficient of the tubewell ownership variable is not significant in either the wheat or the maize yield equation. This indicates that despite increasing groundwater scarcity, as a result of changes in tubewell ownership, agricultural productivity is not adversely affected.

Finally, the analysis demonstrates that farmers earn more money with the shift to private tubewell ownership (Table 3, column 9). The coefficient of tubewell ownership is positive and significant. Although we do not know the exact reason for the rise in income, the result is consistent with the idea that the shift in cropping patterns, from lower-valued wheat to higher-valued cash crops, is the underlying cause.

The effect of groundwater use on equity

To explore the equity effect of groundwater use, a different dataset, one that was larger and included detailed information on income, was analysed. These data come from a randomly selected national sample of 60 rural villages in six provinces (Hebei, Liaoning, Shanxi, Zhejiang, Hubei, and Sichuan). To accurately reflect varying income distributions within each province, we selected one county at random from within each provincial income quintile. The survey team randomly selected two villages within each county and used village rosters and our own counts to choose 20 random households. The village rosters included citizens with and without residency permits (hukou). The survey included a total of 1198 households, and collected data on rural household income that can be disaggregated into cropping, off-farm and other sources. The survey also gathered detailed information on irrigation sources and other household characteristics.

Research results show that irrigation patterns in China differ between regions (Table 4). Most households in the southern provinces irrigated their plots using surface water. For example, 89% of the households in Zhejiang Province only used surface water for irrigation (Table 4, row 12). In northern Hebei province, in contrast, 74% of the households used only groundwater to irrigate their plots (Table 4, row 4). In all six provinces, only a small fraction of the households irrigated the same plot conjunctively (that is, with ground and surface water).

Using our data, the overall Gini coefficient of per capita income from the sample is 0.540 in 2000 (Table 5, row 1, column 2). (The Gini coefficient was developed to measure the degree of concentration (inequality) of a variable in a distribution of its elements. It compares the Lorenz curve of a ranked empirical distribution with the line of perfect equality. This line assumes that each element has the same contribution to the total summation of the values of a variable. The Gini coefficient ranges between zero, where there is no concentration (perfect equality), and unity, where there is total concentration

Table 5. *Gini decomposition by income sources*

	Income sources	(1) S_k	(2) G_k	(3) R_k	(4) $S_kG_kR_k$	(5) $\partial G_0/\partial e_j$	(6) $(\partial G_0/\partial e_j)/G_0$
1	**Total income**	1	0.5359	1	0.5359		
	Cropping income						
2	From irrigated land	0.1713	0.6282	0.3930	0.0423	−0.0495	−0.0924
2a	Surface water	0.1076	0.7367	0.3336	0.0264	−0.0312	−0.0583
2b	Groundwater	0.0603	0.8913	0.2927	0.0157	−0.0166	−0.0309
2c	Conjunctive	0.0035	0.9902	0.0384	0.0001	−0.0017	−0.0032
3	From non-irrigated land	0.0457	0.8504	0.1158	0.0045	−0.0200	−0.0373
4	*Off-farm income*	0.6142	0.7257	0.9096	0.4055	0.0763	0.1424
5	*Other income*	0.1687	0.7708	0.6431	0.0836	−0.0068	−0.0127

S_k, share of income source k in total income. G_k, Gini coefficient of income source k. R_k, Gini correlation between income source k and the distribution of total income. $S_kG_kR_k$, contribution of income source k to the Gini coefficient of total income ($S_kG_kR_k$ of cropping income, off-farm and other income sum to 0.5407). $\partial G_0/\partial e_j$, marginal effect on the Gini coefficient of total income as a result of a marginal percentage increase in income source j. $(\partial G_0/\partial e_j)/G_0$, relative effect of a marginal percentage increase in income source j upon the Gini coefficient of total income.

Table 6. *Gini decomposition by income flows as a result of specific household characteristics*

	Income sources	(1) S_k	(2) G_k	(3) R_k	(4) $S_kG_kR_k$	(5) $\partial G_0/\partial e_j$	(6) $(\partial G_0/\partial e_j)/G_0$
1	Total income per capita (yuan)	1	0.5420	1	0.5420	0	0
	Area of land irrigated by surface water (ha per capita)	0.0214	0.6745	0.1453	0.0021	−0.0095	−0.0175
2	Area of land irrigated by groundwater (ha per capita)	0.0060	0.8676	0.1565	0.0008	−0.0024	−0.0045
3	Level of education of household's labour force (attainment in years)	0.2604	0.2353	0.2552	0.0156	−0.1255	−0.2316
4	Proportion of good quality land (%)	0.0101	0.2383	0.1147	0.0003	−0.0052	−0.0096
5	Cultivated land per capita (ha)	0.0718	0.4759	0.0466	0.0016	−0.0373	−0.0689

This table uses regression results from Table 2. Not all variables are reported for the sake of brevity. S_k, share of income flow contributed by factor k in total household income. Column (1) does not sum to unity because we did not list all explanatory variables in the regression or the residual. G_k, Gini coefficient of income flow contributed by factor k. R_k, Gini correlation between income flow contributed by factor k and the distribution of total income. $S_kG_kR_k$, contribution of income flow contributed by factor k to Gini coefficient of total income. The sum of the five ($S_kG_kR_k$)s does not sum to 0.5572 because we did not list all explanatory variables in the regression or the residual. $\partial G_0/\partial e_j$, marginal effect on Gini coefficient of total income as a result of a marginal percentage increase in income flow contributed by factor j. $(\partial G_0/\partial e_j)/G_0$, relative effect of a marginal percentage change in income flow contributed by factor j to Gini coefficient of total income. The variable area of land irrigated conjunctively by surface water and groundwater is not included in the regression. Only 26 households have plots irrigated conjunctively. If this variable is included in the regression, a serious multicollinearity problem arises between the variable area of land irrigated conjunctively by surface water and groundwater and the constant term.

(perfect inequality) (http://people.hofstra.edu/geotrans/eng/ch4en/meth4en/ch4m1en.html).) Compared with Gini coefficients of 0.28 in 1983 and 0.42 in 1992 as calculated by Rozelle (1996), inequality appears to have continued to rise in the 1990s. The Gini coefficient in rural China, however, is well within the range recorded for rural areas in other developing countries, albeit on the high side. For instance, UNDP (2003) showed that the Gini coefficient in Brazil is 0.61.

Deconstructing the Gini coefficient by income source shows that irrigation (by either ground or surface water) may help to equalize income (Table 6). Cropping income from irrigated land is most equally distributed with a Gini coefficient approximately 0.1–0.2 points lower than those of the other income sources (Table 6, column 2). Cropping income is not concentrated in rich households, as the Gini correlation between cropping income and total income, R_k, is 0.39, a value much lower than that of off-farm income. More saliently, cropping income from irrigated land has the highest marginal effect on lowering inequality (Table 6, column 6). A 1% increase in cropping income from irrigated land for all households would decrease the Gini coefficient for total income by 0.1% (Table 6, row 2). Hence, just as Rozelle (1996) found that cropping income, in general, helped abate regional inequality, our results find that inter-household inequality is attenuated by the presence of irrigation. In contrast, a 1% increase in non-farm income would increase the inequality level by 0.14% (Table 6, row 4). (It should be noted that although the result is statistically significant, it is not highly significant. The main conclusion here is that the data do not support the opposite conclusion; i.e. it is not a negative effect.)

Interestingly, the impacts of different types of irrigation (surface water, groundwater and conjunctive use) are different (Table 5, row 2a–c). Compared with surface water irrigation, the share of cropping income from land irrigated by groundwater in total income is smaller

(Table 5, column 1). Cropping income from land irrigated by groundwater is also less concentrated in rich households, as the Gini correlation between cropping income from land irrigated by groundwater and total income, R_k, is 0.29 (Table 5, column 3). Hence, although cropping income from land irrigated by groundwater is less equally distributed than that from land irrigated by surface water (Table 5, column 2), they have a similar marginal effect on lowering inequality (Table 5, column 6). The Gini coefficient for total income would be lowered by 0.03% (Table 5, row 2b) if cropping income from land irrigated by groundwater increases by 1% and by 0.06% if cropping income from land irrigated by surface water increases by 1%.

Results from deconstructing inequality by income flows as a result of specific household characteristics further confirm irrigation's propensity to equalize income (Table 6). After controlling for other factors, a 1% increase in the area of land irrigated by groundwater would lead to a 0.0045% decrease in the Gini coefficient for total income (Table 6, row 3). A 1% increase in the area of land irrigated by surface water would lead to a 0.0175% decrease in the Gini coefficient for total income (Table 6, row 3). The results also show, however, that irrigation is not the only factor that can decrease inequality. A 1% increase in the education level of the labour force in the household leads to a 0.23% decrease in the inequality level of total income. Hence, education, like irrigation, can lower income inequality.

Concluding remarks

In this paper the authors have sought to demonstrate the evolution of tubewell ownership in the North China Plain and its effect on production and groundwater levels. The results show that since 1990 collective ownership of tubewells has largely been replaced by private ownership. At present, private tubewell ownership has become the dominant form of ownership in many regions. Most private tubewells are still owned jointly by several individuals as shareholding tubewells.

Changes in resource endowments have been shown to lead to changes in commonly observed institutional forms. This shift is consistent with the induced innovation hypothesis (as also is commonly found in other developing economies). Fiscal and financial policies have played important roles in the evolution of tubewell ownership. Because fiscal subsidy programmes have been designed to directly extend funding to single farmers for tubewell investment, the fiscal measures have promoted the emergence of private tubewells. In contrast, targeted bank loan policies that mainly have provided bank loans to village leadership councils for tubewell investment have slowed down tubewell privatization.

The findings also demonstrate that the privatization of tubewells has promoted the adjustment of cropping patterns and increased farmer income while having no adverse impact on crop yield. Such results are consistent with the hypothesis that when tubewell ownership shifts from collective to private (as shown in this paper) and water is more efficiently managed (as shown by Wang *et al*. 2002), producers are able to cultivate relatively high-value crops, which in some cases demand greater attention to timely water supply. Specifically, our results show that after privatization, farmers have expanded the sown area of less water-sensitive and high-value crops, such as maize, cotton and non-cotton cash crops (which are mainly horticultural crops). Importantly, with the shifting of tubewell ownership from collective to private, cropping patterns changed and farmer income increased. Finally, the research results show that groundwater can help to equalize income.

The research presented here indicates that, consistent with the concerns of some observers, the privatization of tubewells *per se* did accelerate the fall in the water table. This result implies that we should be concerned about the rapid fall in the water table. Because of the cropping income effect, we believe that policy makers should continue to support the privatization of tubewells in North China. However, measures should also be taken to address the falling water table; but a return to collective tubewell ownership is not the answer. Other policies, such as pricing and regulatory measures, may need to be used to combat the deterioration of China's groundwater. In fact, given the increased pressure to move into higher valued crops, despite increasing resource scarcity, it seems that the shift to private tubewells will continue. Given their greater efficiency, encouragement of this trend may be warranted, but only when combined with measures to slow the deterioration of the groundwater resource.

Acknowledgements. We acknowledge financial support from the National Natural Science Foundation of China (70733004) and the Knowledge Innovation Program of the Chinese Academy of Sciences (KSCX2-YW-N-039; KSCX-YW-09-04).

APPENDIX: METHOD TO ANALYSE THE EQUITY EFFECT OF GROUNDWATER USE

The total income Gini coefficient is deconstructed by income source. We begin by noting that if y_k is income from source k (e.g. plots irrigated by surface water and plots irrigated by groundwater), then total household income, y_0, is

$$y_0 = \sum_{k=1}^{K} y_k, \ k = 1, \ldots, K. \quad \text{(A1)}$$

It should be noted that the subscripts h and v are suppressed here. Following the method suggested by Stuart (1954), Pyatt *et al*. (1980) and Lerman & Yitzhaki (1985), we can write the Gini coefficient for total household income per capita, G_0, as

$$G_0 = \sum_{k=1}^{K} S_k G_k R_k \quad \text{(A2)}$$

where S_k is the share of y_k in y_0; G_k is the Gini coefficient of y_k; and R_k is the Gini correlation between y_k and the distribution of y_0, defined as

$$R_k = \text{cov}(y_k, F(y_0)) / \text{cov}(y_k, F(y_k)) \quad \text{(A3)}$$

where $F(y_0)$ and $F(y_k)$ are the cumulative distributions of total household income and income from source k, respectively.

If income component j increases by a factor of e, such that $y_j(e) = (1 + e)y_j$ for all households, the marginal effect of this percentage change on total income inequality is

$$\partial G_0 / \partial e_j = S_j(R_j G_j - G_0),\ j = 1, 2, \ldots, K \quad \text{(A4)}$$

where S_j, R_j, G_j and G_0 are measured prior to the marginal income change. Dividing equation (A4) by G_0, we obtain

$$(\partial G_0 / \partial e_j) / G_0 = (S_j R_j G_j) / G_0 - S_j,\ j = 1, 2, \ldots, K. \quad \text{(A5)}$$

The relative effect of a marginal percentage change in source-j income on the Gini coefficient for total income (elasticity of total income inequality with respect to income source j) equals the relative contribution of source j to overall income inequality minus the share of source j in total income. One limitation of this approach is that it does not separate the effect of irrigation from other factors that might be correlated with irrigation; for example, farmers are more likely to adopt irrigation for plots that have better quality. Thus, the quality of land and irrigation status is probably correlated.

The limitation of decomposing inequality by income sources can be overcome by using a regression-based approach to decompose total income inequality by income flows attributable to specific household characteristics. This approach follows the work of Taylor (1997) and Morduch & Sicular (2002). In the first step, a regression is run to estimate income flows:

$$y_{hv} = \alpha + \mathbf{D_{hvw}}\gamma_\mathbf{w} + \mathbf{X_{hv}}\boldsymbol{\beta} + \mathbf{P_v}\boldsymbol{\theta} + \mathbf{Z_v}\boldsymbol{\delta} + \mu_v + \varepsilon_{hv} \quad \text{(A6)}$$

where y_{hv} denotes total household income per capita for household h in village v and θ is the constant variable that influences household income. $\mathbf{X_{hv}}$ is a matrix of household characteristics including household size, average age and education level of the household's labour force, degree of land fragmentation, proportion of high-quality land and proportion of land affected by negative shocks. Cultivated land per capita is included to control for land as a fixed input. We also have included several variables, household agricultural assets, self-employed business assets, livestock assets and non-productive assets (in per capita terms), to control for factors including household access to credit markets or ability to adopt new technologies. The matrix $\mathbf{P_v}$ denotes the prices facing farmers within each village, including both variable input prices and output prices. $\mathbf{Z_v}$ denotes the observable village characteristics including a community's topography, its distance from the county seat, the number of telephones per capita in the village and the proportion of villagers who out-migrated to destinations outside the village or worked off-farm in the local wage-earning market in 1990. Equation (A6) also includes a term, μ_v, which represents all other community fixed effects that vary by village and that are difficult to observe or measure (e.g. the economic environment of the village, certain climatic and/or agronomic factors that affect village-wide yields and prices, etc.). After holding $\mathbf{X_{hv}}$ and $\mathbf{Z_v}$ constant, γ_v can be interpreted as our parameters of interest, measuring the effect of area of irrigated land per capita denoted by $\mathbf{D_{hvw}}$. When $w = 1$, $\mathbf{D_{hvw}}$ denotes the area of land irrigated by surface water. When $w = 2$, $\mathbf{D_{hvw}}$ denotes the area of land irrigated by groundwater. When $w = 3$, $\mathbf{D_{hvw}}$ denotes the area of land irrigated conjunctively by surface water and groundwater. It should be noted that a linear specification for equation (A6) is required to decompose the inequality by estimated income flows.

References

Barker, R. & Molle, F. 2005. Perspectives on Asian irrigation. *In:* Shivakoti, G.P., Vermillion, D.L., Wai-Fung, L. et al. (eds) *Asian Irrigation in Transition-Responding to Challenges*. Sage Publications, New Delhi, 45–78.

Bromley, D.W. 1992. *Making the Commons Work: Theory, Practice and Policy*. Institute for Contemporary Studies Press, San Francisco, CA.

Brozović, N., Sunding, D.L. & Zilberman, D. 2006. Optimal management of groundwater over space and time. *In:* Goetz, R.-U. & Berga, D. (eds) *Frontiers in Water Resource Economics*. Springer, New York, 275.

Chen, J. & Liu, Y. 2008. Development of North West China. World Wide Web Address: http://www.cass.net.cn/zhuanti/y_xibei/ [in Chinese].

China National Bureau of Statistics 2002. *China Statistical Yearbook*. China Statistic Publishing House, Beijing.

Fujiie, M., Hayami, Y. & Kikuchi, M. 2006. The conditions of collective action for local commons management: The case of irrigation in the Philippines. World Wide Web Address: http://www.fasid.or.jp/english/surveys/research/program/research/pdf/discussion/2002-002.pdf.

Hebei Hydrological Bureau and Water Environmental Monitor Center 1999. *Hebei Water Resources Assessment*. Hebei Water Resource Bureau, Shijiazhuang.

Hong, F., Zhang, Z., Zhang, F., Sheng, C., Yu, C. & Wang, Z. 2008. The study of water resources variation of North China Plain. World Wide Web Address: http://old.cgs.gov.cn/zt_more/34/zhaiyao/html/01/128.htm.

Kendy, E., Zhang, Y., Liu, C., Wang, J. & Steenhuis, T. 2004. Groundwater recharge from irrigated cropland in the North China Plain: case study of Luancheng County, Hebei Province, 1949–2000. *Hydrological Process*, **18**, 2289–2302.

Lerman, R.I. & Yitzhaki, S. 1985. Income inequality effects by income sources: a new approach and applications to the US. *Review of Economics and Statistics*, **67**, 151–156.

Meinzen-Dick, R. 1996. *Groundwater Markets in Pakistan: Participation and Productivity*. International Food Policy Research Institute, Research Reports, **105**.

Ministry of Water Resources 2006. *China Water Resources Bulletin*. World Wide Web Address: http://www.chinawater.net.cn/cwsnet/gazette-new.asp.

Morduch, J. & Sicular, T. 2002. Rethinking inequality decomposition, with evidence from rural China. *Economic Journal*, **112**, 93–106.

Ostrom, E. 1990. *Governing the Commons: the Evolution of Institutions for Collective Action*. Cambridge University Press, New York.

Otsuka, K. 1995. *Land Tenure and Forest Resource Management in Sumatra: Analysis Issues and Research Policy for Extensive Survey*. MP 11. IFPRI, Washington, DC.

Pyatt, G., Chen, C. & Fei, J. 1980. The distribution of income by factor components. *Quarterly Journal of Economics*, **95**, 451–473.

Rozelle, S. 1996. Stagnation without equity: patterns of growth and inequality in China's rural economy. *China Journal*, **35**, 63–92.

Shah, T. 1993. *Groundwater Markets and Irrigation Development: Political Economy and Practical Policy*. Oxford University Press, Mumbai.

Stuart, A. 1954. The correlation between variate-values and ranks in samples from a continuous distribution. *British Journal of Statistical Psychology*, **12**, 37–44.

Tang, S. 1991. Institutional arrangements and the management of common-pool resources. *Public Administration Review*, **51**, 42–51.

Taylor, J.E. 1997. Remittances and inequality reconsidered: direct, indirect, and intertemporal effects. *Journal of Policy Modeling*, **4**, 187–208.

UNDP 2003. *Human Development Report*. United Nations Development Program. United Nations, New York.

Uphoff, N. 1986. *Local Institutional Development: An Analytical Sourcebook with Cases*. Kumarian Press, West Hartford, CT.

Wang, J., Huang, J. & Rozelle, S. 2002. Groundwater management and tubewell technical efficiency. *Journal of Water Sciences Advances*, **13**, 259–263 [in Chinese].

Wang, J., Huang, J. & Rozelle, S. 2005. Evolution of tubewell ownership and production in the North China Plain. *Australian Journal of Agricultural and Resource Economics*, **49**, 177–195.

Wang, J., Huang, J., Rozelle, S., Huang, Q. & Blanke, A. 2007. Agriculture and groundwater development in Northern China: trends, institutional responses, and policy options. *Water Policy*, **9**, 61–74.

Wang, S. 2007. Recent trends in poverty in PRC. World Wide Web Address: http://www.adbi.org/discussion-paper/2004/01/04/83.poverty.targeting/recent.trends.in.poverty.in.prc/.

Wang, X. 2008. Water scarcity in Hebei. World Wide Web Address: http://www.yzdsb.com.cn/20040315/ca338813.htm [in Chinese].

White, A. 1995. *Conceptual Framework: Performance and Evolution of Property Rights and Collective Action*. MP 11. IFPRI, Washington, DC.

Zhang, Z. 2005. Groundwater in the vast North China Plain. *Chinese Journal of Nature*, **26**, 311–314.

Received 2 February 2009; accepted 25 May 2009.