Available online at www.sciencedirect.com
SCIENCE DIRECT®
Food Policy 31 (2006) 30–52
FOOD POLICY
www.elsevier.com/locate/foodpol

Irrigation, agricultural performance and poverty reduction in China

Qiuqiong Huang [a,*], Scott Rozelle [a], Bryan Lohmar [b], Jikun Huang [c], Jinxia Wang [c]

[a] *Department of Agricultural and Resource Economics, University of California, Davis, CA 95616, United States*
[b] *Economic Research Service, United States Department of Agriculture, United States*
[c] *Center for Chinese Agricultural Policy, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, China*

Abstract

The overall goal of our paper is to understand the impact that irrigation in China has had on grain production and incomes, in general, and income and poverty alleviation in poor areas, in particular. The paper seeks to meet three objectives. First, we describe the relationship among irrigation status, yields and household crop revenue. Second, we seek to understand the magnitude and nature of the effect that irrigation has on yields and crop revenue. Finally, we seek to understand the impact that irrigation has on incomes in poor areas. Our analysis shows that irrigation contributes to increases in yields for almost all crops and in income for farmers in all areas. The importance of crop income in poor areas and the strong relationship between crop revenue and irrigation provides evidence of the importance of irrigation in past and future poverty alleviation in China. We also show that in the majority of the villages that invested in new irrigation, returns are positive even after accounting for increases in capital and production costs.

Keywords: Irrigation; Fixed effects; Production; Income; Poverty

* Corresponding author. Tel.: +1 530 752 6770; fax: +1 530 752 5614.
E-mail address: huang@primal.ucdavis.edu (Q. Huang).

0306-9192/$ - see front matter
doi:10.1016/j.foodpol.2005.06.004

Introduction

China has made remarkable progress in achieving rapid growth in grain and food production and increasing the standard of living in its rural areas since the onset of economic reform (Huang et al., 1999; Lardy, 1983; Putterman, 1993; World Bank, 2001a,b). By 2000, China's farmers were producing more than 3000 kcal per capita annually. China has been a net exporter of food since 1983 and since 2000 was increasingly a net grain exporter (Huang et al., 2004). The total factor productivity (TFP) of grain increased steadily during the 1980s and 1990s (Jin et al., 2002). From 1978 to 2000, more than 200 million people in rural areas have escaped from poverty.

In accelerating production growth and poverty reduction, one type of investment that China's leaders have always relied on has been water control. China's success in achieving food self-sufficiency took place when China's government made massive investments in irrigation infrastructure in the 1960s and the 1970s, suggesting that irrigation has played a key role in rural development in the past (Liao, 2003). In fact, investment in water control dominates all other forms of investment. For example, China's government invests more than 10 times as much in irrigation (30% of the total expenditure in rural China in 2000) as it does in agricultural research (only 2.2% – Fan et al. (2004)). Spending on water control (83 billion yuan) also far exceeds the annual budget that is targeted specifically at poverty reduction (22.4 billion). Irrigation investment tends to be the most important form of agricultural investment in both rich and poor areas (Ministry of Water Resource, 2001; National Statistical Bureau of China, 2001a,b).

Despite this record, it remains unclear that whether China's massive spending on water control, and the irrigation infrastructure that it has spawned, leads to either enhanced performance in the agricultural production or improvements in the livelihood of the poor. Likewise, it is unclear if more money should be spent in the future. Despite the common perception of the effectiveness of irrigation investment, many empirical studies fail to find a strong linkage between irrigation and production and/or incomes. Inside China, Hu et al. (2000) find that irrigation (measured as the ratio of irrigated land to cultivated land) did not contribute to TFP growth of rice in China between 1980 and 1995; Jin et al. (2002) extend the work to other crops and cannot find a link between irrigation and TFP growth of any major grain crop (rice, wheat or maize); using a provincial level data set, Zhu (2004) finds that irrigation does not have any impact on the yield of wheat or maize between 1979 and 1997; using a county level data set, Travers and Ma (1994) demonstrate that returns from irrigation investments in the poor counties are lower than their costs.

Internationally, the record is mixed. Studies on other countries frequently find insignificant effects or low returns of irrigation. For example, Fan et al. (1999) show that although levels of investment in water control exceed those of seven other investment categories, irrigation ranks only sixth in terms of marginal impact on poverty alleviation in India behind investments, such as, rural roads, agricultural research and education. Rosegrant and Evenson (1992) also find that irrigation does not have a significant impact on TFP in India. Other studies have found positive effects (Bhattarai et al., 2002; Dhawan, 1988; Roy and Shah, 2003). For example, Bhattarai et al. (2002) found that irrigation increases cropping intensity and thus crop revenue per hectare in Vietnam, India and Sri Lanka.

As China enters the 21st century, the nation continues to face a challenge of meeting the nation's food security, income growth and poverty reduction goals (China Council for International Cooperation on Environment and Development, 2004). Since significant increases in public rural investment are uncertain, leaders will have to give greater emphasis to using their public investment resources more efficiently. As a consequence, research is needed to find which type of investment can help China achieve its policy goals in a fairly efficient manner. The overall goal of our paper is to understand the impact that irrigation in China has had on grain and food production and incomes, in general, and poverty alleviation in poor areas, in particular. To meet this overall goal, we have three specific objectives. First, we describe the relationship between irrigation status, and yields and household crop revenue. Second, we seek to measure the magnitude and nature of the impact that irrigation has on yields and crop revenue. Finally, we seek to understand the impact that irrigation has on incomes in poor areas and compare them to the costs associated with increasing income from irrigation.

To meet these objectives, in this paper we take an approach that differs from those used in previous studies. First, unlike most studies that used rough proxies for irrigation, we look directly at the relationship between the stock of irrigation (that is, the availability of irrigation at the plot level), crop yields and crop revenues. Second, by using a fixed effects estimating framework, we are able to control for the unobserved heterogeneity that may obscure the relationship between irrigation, crop yields and crop revenue. Most studies fail to do so. Third, by using plot level data, we account for variation in plot-specific factors that may affect crop yield such as soil quality. We also divide the observations in our study into rich and poor households (or households in rich and poor areas). Unlike the findings that have been shown by others in the literature (e.g., Travers and Ma, 1994), our results demonstrate that irrigation contributes to growth in production and increases the welfare of poor farmers more than it does rich farmers.

The rest of the paper will be organized as follows. In the first section, we introduce the data that are used for the analysis. The following section illustrates the proportion of cultivated area that is irrigated and the unconditional differences between irrigated and non-irrigated yields and per hectare crop revenues. To our knowledge, this is the first set of *by crop* estimates of sown area and yields for *irrigated area and for non-irrigated areas* in China, a statistic that, while commonly available in most other countries, has not been in China. After explaining the framework for examining the impact of irrigation, we present the results of our multivariate analyses in the fourth section: we first seek to explain the impact of irrigation on yields and revenues, centering our attention on poor areas. We also demonstrate the possible bias in the estimating approach that uses aggregate data. In the following section we conduct a cost–benefit analysis of irrigation. The final section concludes.

Data description

The main set of data for our study comes from a randomly selected, nationally representative sample of 60 villages in 6 provinces (Hebei, Liaoning, Shaanxi, Zhejiang, Hubei, and Sichuan) of rural China (henceforth, the China National Rural Survey or CNRS). To reflect accurately varying income distributions within each province, we selected randomly one county from within each income quintile for the province, as measured by the gross value of industrial output (GVIO).[1] The survey team selected randomly two villages within each county and used village rosters to choose randomly 20 households, both those with their residency permits (*hukou*) in the village and those without. The survey included a total of 1199 households. The survey was conducted by Center for Chinese Agricultural Policy (CCAP).

The survey collected a wide range of information on the household's production activities, and included a special block that focused on collecting by-plot information. On average, each household cultivated four plots. For each plot, the respondent recounted crops that were grown during the sample year and the plot's irrigation status (was it irrigated by surface water, by groundwater, conjunctively by surface water and groundwater, or neither). In addition, enumerators collected a number of other plot attributes including: soil quality, topography, plot size, cultivation intensity, distance of the plot from the household, and a measure of any shock (e.g., flood or drought) that hit the plot during the year.

Irrigation, crop choice, and agricultural performance

Compared to other countries in the world, the proportion of China's cultivated area that is irrigated is high (Table 1). Data from our survey show that 52% of cultivated land is irrigated (row 1). Of the area that is irrigated, farmers irrigate 61% with surface water and the rest with groundwater. Although the figure for the proportion of irrigated area is higher than that published by National Statistical Bureau

[1] In choosing our sample, our objective was to choose a sample that contained a range of observations on households from poor to rich. Although we could have used rural per capita income to stratify the sample, there are several problems with doing so. Rural per capita income measures based on the information from the annual Household Income and Expenditure Survey of China's National Bureau of Statistics are only calculated at the provincial level (since only a fraction of counties, townships and villages are included in the sample). An alternative source of per capita income data, the government's annual census of villages that is reported up through the government hierarchy, does create estimates of rural per capita income for most villages. However, there are serious reporting problems with these measures (Park and Wang, 2001). According to our experience, rich villages sometimes tend to under-report income per capita and poorer villages sometimes tend to over-report. If this is so, the distribution of per capita incomes based on these data would be artificially compressed and provide a less powerful stratification scheme. In response to these shortcomings, we use per capita gross value of industrial output (GVIO) since we believe that industrial output in a township or village is more observable and, hence, likely to be more accurately measured. Moreover, GVIO is highly correlated with rural incomes (Rozelle, 1996). Finally, in the townships (rarely) and villages (sometimes) in which GVIO is not available, we have found it is relatively easy for officials to rank townships in terms of their level of industrialization.

Table 1
Proportion of sown area by irrigation type (%)

	(1) Irrigated area[a]	Among irrigated area		(2) Non-irrigated area
		(1a) Surface water area	(1b) Ground water area	
China	52	61	37	48
Major grains-aggregate				
Rice	95	95	3	5
Wheat	61	34	63	39
Maize	45	31	65	55
Major grains – by season				
Single season rice	94	94	4	6
Early season rice	99	99	0	1
Late season rice	99	99	0	1
Single season wheat	10	37	63	90
Wheat–rice rotation	98	96	2	2
Wheat–maize rotation	77	24	73	23
Wheat–other crop rotation	63	23	76	37
Single season maize	15	23	71	85
Maize–other crop rotation	49	72	27	51
Coarse grains[b]	28	26	71	72
Tubers[c]	40	88	10	60
Cash crops				
Cotton	94	13	87	6
Peanut	69	8	92	31

Source: Authors' survey.
[a] Proportion of irrigated areas include areas irrigated by surface water, by groundwater and by both (conjunctively). Proportion of areas irrigated conjunctively is not reported here because it is less than 3%. Thus column (1a) and column (1b) does not sum up to 100%.
[b] Coarse grains include sorghum, millet, pearl millet, buckwheat and others.
[c] Tubers includes white potatoes and sweet potatoes.

of China (CNSB, 2001), both are higher than most of other countries in the world.[2] For example, the comparable statistic for India is 33%, for Brazil is 1% and for the US is 6% (Food and Agriculture Organization of the United Nations, 2002).

Most importantly, China's major food grains are mostly irrigated (Table 1, rows 2 and 3). Around 95% of rice and 61% of wheat are irrigated, levels that are above the national average. Henceforth, as shown in Huang et al. (1999), investment in irrigation have been central for China to maintain food security and will continue to be

[2] Our figure may be higher than that used by official statisticians for two reasons. First, in our sample, we do not choose those villages that are more than 4 h away from township so we are missing the set of sample households that would be from an area in which the proportion of irrigated cultivated area was lower than average. This would make our number biased upward. In addition, although almost a representative sample of China, our randomly selected sample did not choose some provinces that happen to be less irrigated than the average national level. For example, only 17% of cultivated land in Heilongjiang province is irrigated, only 27% in Inner Mongolia and 19% in Gansu (National Statistical Bureau of China, 2001a,b).

one investment that enables China to lift its future production of food and meet its food grain security goals of achieving 95% self-sufficiency for all major grains.

While around a half of China's cultivated area is irrigated, the proportion of area that is irrigated varies sharply by crop. In contrast to the case of food grains, a majority of area for most feed grains and lower-valued staple crops is not irrigated (Table 1, rows 4, 14, and 15). Despite its growing importance in China's agricultural economy, only 45% of China's maize is irrigated and even a lower proportion of coarse grains and tubers (including white and sweet potatoes) are irrigated. Although the proportion of irrigated area in cash crops also varies by crop, most of the area of China's main cash crops is irrigated (e.g., 94% of cotton area and 69% of peanut area).

Our descriptive statistics show that irrigation may contribute to the growth in crop production in at least two ways. First, irrigation helps increase crop yield. The positive and significant differences between yields of irrigated and non-irrigated plots indicate that for almost all crops (except for rice and tubers) the average yields of irrigated plots exceed significantly those of non-irrigated ones (Table 2, column 6). For example, wheat yields of irrigated plots are 70.9% higher than those of non-irrigated ones (row 2). Irrigated maize yields are 16.4% higher and irrigated cotton yields are 177% higher (rows 3 and 20).

Second, irrigation improves crop production by increasing the cultivation intensity and, as a result, the *annual output* of a particular plot of land (Table 2).[3] When two crops are planted in rotation with one another (rows 5–7; rows 9–15 and row 17), the annual output per plot rises steeply when compared to the yields of a single season crop (rows 4, 8, and 16). For example, the annual yields of wheat–rice (9266 kg/ha – with the yield of rice being 6327 and that of wheat being 2939), and wheat–maize (8263 kg/ha – with the yield of wheat being 3877 and the yield of maize being 4386) rotations far exceed those of single season wheat (1931), rice (6195) and maize (2876).

In the course of increasing crop production, irrigation almost certainly also helped improve food security at household level, especially for poor households. In our analysis we define poor households and rich households as those with household incomes in the bottom and top quintile of each province respectively. Our data show that poor households rely more on grain production. Among poor

[3] Although there are two crops (rice and tubers) that have lower yields in irrigated plots when compared to non-irrigated plots, closer inspection shows that even in these cases, irrigation increases yields or at least does not hurt them (Table 2, rows 1 and 19). If we divide rice into single-season rice, rice grown in a rice–rice rotation (early season rice and late season rice) and rice grown in a wheat–rice rotation, we find for each of this subdivision, the differences between the yields of irrigated and non-irrigated plots are all positive and significantly differently in several cases. The average yields of irrigated rice plots in the aggregate are lower because yields of single-season rice (both those that are irrigated and non-irrigated) are 64% higher than those of other types of rice (rice grown in rice–rice or wheat–rice rotations). In the case of tubers, we find that the higher yields on non-irrigated plots can be accounted for by plots in sample's three southern provinces (Zhejiang, Sichuan and Hubei Provinces) since the main season for growing tubers coincides with the rainy season and tubers planted in irrigated areas that are typically more subjected to flooding do not do as well as those planted on non-irrigated plots.

Table 2
Crop yield by irrigation type (unit: kg/ha)

	(1) Total yield	(2) Irrigated yield[a]	(3) Surface water yield	(4) Ground water yield	(5) Non-irrigated yield	(6) Percentage increase[b]
Major grains – aggregate						
Rice	5947	5942	5919	6663	6002	−1.0
Wheat	3305	3853	3302	4518	2255	70.9***
Maize	4041	4378	4276	4522	3762	16.4***
Major grains – by season[c]						
Single season rice	6195	6207	6202	6367	6087	2.0
Rice–rice rotation	9934	9949	9943	11,250	9000	10.5
Early season rice	4516	4516	4513	5250	4500	0.4
Late season rice	5418	5433	5431	6000	4500	20.7***
Single season wheat	1931	3624	4025	3223	1698	113.4***
Wheat–rice rotation	9266	9284	9251	11,357	7513	23.6
Wheat	2939	2949	2972	3000	1763	67.3***
Rice	6327	6334	6279	8357	5750	10.2***
Wheat–maize rotation	8263	9174	8309	9617	6271	46.3***
Wheat	3877	4439	3796	4746	2642	68.0***
Maize	4386	4735	4514	4872	3628	30.5***
Wheat–other crop rotation	3331	3926	3375	4212	2411	62.8***
Single season maize[d]	2876	3720	3056	4309	2378	56.4***
Maize–other crop rotation	3941	3984	4181	2,883	3893	2.3
Coarse grains	1457	1996	1836	2115	1119	78.3***
Tubers[e]	4631	3918	4072	2942	5141	−23.8***
Cash crops						
Cotton	2357	2561	1190	2790	924	177.3***
Peanut	2538	2758	2731	2770	2143	28.7***

Source: Authors' survey.
[a] We did not include yield of the plots irrigated by surface water and ground water conjunctively because there are few observations of them.
[b] Percentage increase means irrigated yield compared to non-irrigated yield. We also test whether the difference is statistically significant.
[c] In this category, we divide rice into single season rice, double season rice (early season rice, late season rice). We divide wheat into single season wheat, wheat–rice rotation, wheat–maize rotation and wheat rotated with other crops than major grain. We divide maize into single season maize and wheat–maize rotation.
[d] We dropped Liao Ning province here because 80% are non-irrigated plots. 46% of the non-irrigated plots and 60% of the irrigated plots suffered from draught (lost of produce more than 50%).
[e] Tuber includes sweet potato and white potato.
*** Indicates significant at 99% level.

households, 78% of the land of is allocated to growing grain crops, a level that is nearly 10% higher than that among rich households (68%). By increasing the level of grain output, irrigation also contributed to better access to food for poor households.

Even larger differences appear when examining *differences between the level of revenue* (price times yields) earned by farmers on their irrigated and non-irrigated plots (Table 3). Overall revenue from irrigated plots is 79% higher than that of non-irrigated plots (row 1, column 6). While we can not pinpoint the source of these changes, three factors account for the higher crop revenues of a plot when irrigation is introduced: higher yields (of same crop), increasing intensity (producing more than one crop per season), and shifts to higher valued crops that are possible after irrigation.

Table 3
Gross crop revenue by irrigation type and China's regions

	(1) Annual income per capita (yuan/person)	(2) Percentage of crop income in total income (%)	(3) Crop revenue (yuan/ha)	(4) Crop revenue for irrigated plots (yuan/ha)	(5) Crop revenue for non-irrigated plots (yuan/ha)	(6) Percentage increases of crop revenue[a] (%)
China	1980	20[b]	3940	4585	2568	79[b]
By wealth level[c]						
Rich area	3166	10	4060	4603	2439	89
Poor area	1173	34	3318	4385	2268	93

Source: Authors' survey.
[a] Percentage increase is calculated as (column 4–column 5)/column 5.
[b] The national level is lower than both in rich and poor areas because we do not include middle-income area here that has 65% increases in crop revenue when plots are irrigated.
[c] Rich area includes households whose incomes rank the first 20 percentile in every province and all the households from Zhejiang province. Poor area means households whose incomes rank the last 20 percentile in every province.

Finally, our results also provide evidence that if new irrigation may help raise incomes in poor areas.[4] Farmers in rich and poor areas earn higher revenue from their irrigated crops (rows 2 and 3). In rich areas crop revenue per hectare from irrigated plots is 89% higher than that from non-irrigated plots. In poor areas revenue from irrigated plots exceeds those of non-irrigated ones by 93%.

While the data show that irrigation is effective in both rich and poor areas, differences in the nature of rich and poor economies suggest that irrigation may have larger impacts on rural welfare in poor areas. Since people are poorer, and since we typically assume that utility functions are concave, if rich and poor areas enjoy equal income gains, the gains in the poorer areas will turn into larger increases in welfare. As seen above, crop revenues in the poorest areas (93%) increase slightly more than those in richer areas (89%). Moreover, crop revenues make up a much larger part of total household income in poor area than in rich areas (only 10% in rich areas and more than 30% in poor areas – column 2). If we multiply the percentage increase of crop revenue by the share of crop revenue in total income, increases in total income in rich areas will be lower than that in poor areas. Since China's poverty is typically characterized by the small gap between the income of the poor and the poverty line (World Bank, 2001a,b), raising the income of the poor by more than one-third would

[4] To directly address the positive impact of irrigation on household income, we should have used crop income and analyzed the impact of irrigation on crop income, and then linked it to household income. Unfortunately, although information on yield, irrigation status and other variables is collected at the plot level, information on cost of inputs including fertilizer, labor, machinery and seedling is only collected at the household level. Hence it is impossible for us to obtain the crop income at the plot level and carry out such analysis. However, in the cost–benefit analysis of irrigation, we show that, *in the majority of the villages that invested in new irrigation*, the benefit of increasing irrigated area outweighs the cost of doing so. In addition, another study that also uses the same data set (Huang et al., in press), shows that increases in irrigated area increases household income through its positive impact on household crop income. In summary, even given the limitations of our analysis, we believe the evidence is clear that increasing irrigation will increase the total income of household.

almost certainly have the effect of pulling a vast majority of those in newly irrigated areas out of poverty.

Framework for examining the effect of irrigation on production

All the findings from our descriptive analysis support one fact: irrigation has substantial benefits for farmers, especially the poor ones. Such findings, however, are curious given the inability of previous studies to find significant effects of irrigation on agricultural performance. One possible reason is that our descriptive statistics only revealed simple correlations between irrigation and crop yields and crop revenues, while the underlying relationship might be disguised by the relationship between yield and other factors that are positively correlated with irrigation (e.g., soil quality).

Alternatively, several weaknesses in previous studies may also account for the conflicting findings. First, due to lack of data, most studies have only used rough proxies for irrigation, such as government expenditure on irrigation. These proxies, however, may not provide an accurate measure of irrigation because there is no guarantee that the allocation of funds to water control is ever turned into an effective increase in irrigation stock. Moreover, the addition of irrigated area (and the subsequent rise in yields) through public investment likely will occur only at a lag of a year or more after the investment is made. Therefore, to analyze the impact of public investment, a dynamic framework or times series data is needed (see for example, Rosegrant and Kasryno, 1994). Most studies that look at public investment have only used a static framework and so do not account for such an investment lag.

Second, and most importantly for this type of study, most other researchers do not control for the unobserved heterogeneity that may be obscuring the relationship between irrigation and crop yields and crop revenue. For example, the inability to control for the household's off-farm employment opportunities could lead to an underestimation of the impact of irrigation on yield in rich areas (e.g., Zhejiang province). Although the proportion of irrigated land might be higher in Zhejiang than in poorer provinces, households in richer areas have more opportunity to work off-farm and, ceteris paribus, they will almost certainly allocate less family labor to farming activities than households in poorer provinces that do not have as convenient access to off-farm jobs. An omitted variable problem, in this case the omission of off-farm employment opportunities, would make the estimated relationship between irrigation and agricultural performance unreliable (Kennedy, 1998).

Finally, most analyses have been highly aggregated, both across provinces and across crops (Travers and Ma, 1994; Zhu, 2004). Using aggregate data fail to account for variation in plot-specific factors that may affect crop yields. For example, failure to account for the variation in soil quality will cause a downward bias in the estimation of the coefficient on irrigation. The reason is that that the plots of highest qualities are more likely to be irrigated first. In later years, when opening up newly irrigated area, the land that is brought into cultivation is lower quality. Because of this, it is possible that the *average* yield could fall when it is evaluated at an aggregate level.

In our analysis, we take a different approach to explore the relationship between irrigation and agricultural performance which addresses the shortcomings of previous work. First, our strategy is to look directly at the relationship between irrigation and crop yields and crop revenues. When we use the stock of irrigation itself (that is, whether the plot is actually irrigated during each season being analyzed), we avoid the need to use a proxy for irrigation. In addition, in our study we have collected information on approximately four plots for each sample household. Such data allow us to control for all of the non-plot varying factors that could be affecting yields (such as off-farm employment opportunities) by using a fixed effects framework. Finally, by using a rich set of plot level data, we can hold constant many of the plot-specific factors that could be affecting yields and which could be potentially correlated with a plot's irrigation status (such as, soil quality).

To measure the effect of irrigation on yields while holding other factors constant, we start from the basic model below to explain the *supply response* of farmers that are producing a specific crop

$$y_{ih} = \alpha + \gamma D_{ihj} + \mathbf{X}_{ih}\boldsymbol{\beta} + \mathbf{P}_h\boldsymbol{\theta} + \boldsymbol{\mu}_h + \varepsilon_{ih}, \tag{1}$$

where y_{ih} denotes the yield (of a specific crop) or the revenue of the ith plot of the hth household. The term, $\mathbf{X}_{ih}$, denotes plot-specific characteristics: *soil quality* (where soil quality is a subjective measure whereby if the farmer ranked his plot as 'good,' a dummy variable was set equal to 1; and was zero if the farmer ranked his plot as 'not very good' or 'poor'); *topography – plain* (a dummy variable that was set equal to 1 if the plot was on a plain); *topography – hill* (a dummy variable that was set equal to 1 if the plot was on a hill); *plot size* (measured in μm); *distance from home* (the distance of the plot from the farmer's house, measured in km); *shock-severity of disaster* (a continuous variable based on the farmer's subjective opinion about the percentage reduction in yields on each plot caused by adverse weather shocks suffered during the survey year); *single season crop* (a dummy variable that was set equal to 1 if the crop is not grown in conjunction with other crops during the year and 0 otherwise).[5] The parameters, $\boldsymbol{\beta}$, represents a vector of parameters that correspond to the effects of the plot-specific variables have on yields. The vector, $\mathbf{P}_h$, denotes the prices facing a household, including both input and output prices, and $\boldsymbol{\theta}$ is the parameter that relates prices to yields. Eq. (1) also includes a term, $\boldsymbol{\mu}_h$, which represents all non-plot factors including both observable variables (household land holdings, the distance of a village to the county seat) and unobservable variables (e.g., the household's off-farm employment opportunities and management ability).

Our variable of interest is D_{ihj}, a plot's irrigation status. It is written with an additional subscript, j, because in some of our specification we want to allow for a

[5] Because we use a supply-function approach, we do not include measures of other variable inputs.

disaggregation of irrigation between surface ($j = 1$) and groundwater ($j = 2$).[6] When the variable is written without a subscript, irrigation is a variable that represents irrigation regardless of whether it is from surface or groundwater sources. Holding other variables constant, the parameter γ can be interpreted as our parameter of interest, measuring the effect of irrigation on yields.

Estimating Eq. (1) has both strengths and weaknesses. It enables us to estimate the effects of specific household and village characteristics such as household landholdings and assets, prices and village topography on yields or revenue. However, the inclusion of such variables only helps absorb part of the heterogeneity in the dependent variable. Moreover, no matter how many household and village variables we include, there almost certainly may be many factors that, although unobservable, may both affect yield and be correlated with the variable of interest, irrigation. One such example is the bias of the OLS estimate caused by omission of the off-farm employment opportunities that we mentioned above.

One solution to the problem is to include in place of the variables in $\boldsymbol{\mu}_h$, a set of 1198 household indicator variables that capture all of the observed and unobservable heterogeneity. The major benefit of this specification is to remove all household and village effects that may affect a plot's production. Casting the problems in this way (as a fixed effects model), however, means that we cannot separate the effect of specific village characteristics ($\mathbf{P}_h$ and $\boldsymbol{\mu}_h$) from other village fixed effects since all are captured by the village dummy variables. In addition, since input and output prices are almost surely the same within each village (Huang et al., 2004), the effect of prices on income is also grouped with other village fixed effects and cannot be separated out. However, to include the specific household and village variables including prices in the model, we would have to move away from the fixed effects framework and thus not be able to control for the unobserved heterogeneity. This will cause bias in the estimation of coefficients. Since coefficients on specific household and village characteristics are not the focus of our paper and using a fixed effects framework enhances greatly the performance of the estimation, we adopt this approach and the fixed effects model that we estimate is

$$y_{ih} - \bar{y}_i = \alpha + \gamma(D_{ihj} - \overline{D}) + (\mathbf{X}_{ih} - \overline{\mathbf{X}})\boldsymbol{\beta} + (\mathbf{P}_h - \overline{\mathbf{P}})\boldsymbol{\theta} + (\boldsymbol{\mu}_h - \bar{\boldsymbol{\mu}}) + (\varepsilon_{ih} - \bar{\varepsilon}), \quad (2)$$

[6] When irrigation is used to explain crop yield or crop revenue, an endogeneity problem may exist in terms of the household-level choice of which crop to irrigate. In the case of rural China, the decision on which crop to irrigate is most likely to be exogenous to our model. First, whether a plot is irrigated or not largely depends on whether irrigation is available. In most parts of our sample, if irrigation water is available, it is used. It depends on whether the plot is located in the command area of a well in the case of groundwater irrigation and on whether the plot is located within the reach of a canal. In the case of surface water irrigation. Second, the choice of which crop to cultivate depends on the cropping cycle and the characteristics of the plot. To look at this issue more closely, we use the part of our data that collected information on the types of crops grown on the plot one year before the survey year. We find that households grow the same summer crop on 95% of plots in each of two consecutive years. Moreover, to examine this issue more rigorously, we perform a Hausman–Wu test. The result of the test failed to reject the null hypothesis that the variable irrigation is exogenous to our model.

where $\bar{y}$, $\overline{D}$, $\overline{\mathbf{X}}$, $\overline{\mathbf{P}}$, $\bar{\boldsymbol{\mu}}$ and $\bar{\varepsilon}$ denote the average of the variables at the household level.

Since $\mathbf{P}_h - \overline{\mathbf{P}} = 0$ and $\boldsymbol{\mu}_h - \bar{\boldsymbol{\mu}} = 0$, Eq. (2) can be simplified to

$$y_{ih} - \bar{y} = \alpha + \gamma(D_{ihj} - \overline{D}) + (\mathbf{X}_{ih} - \overline{\mathbf{X}})\boldsymbol{\beta} + (\varepsilon_{ih} - \bar{\varepsilon}). \tag{3}$$

Although prices are not explicitly included in Eq. (3), it should be noted that we are holding the effect of price constant (with the inclusion of village dummies) and are estimating a supply function. When using cross-sectional data, it is common *not* to include price explicitly in the analysis since there often is no variation in prices within the unit for which fixed effects are controlled (Lau and Yotopoulos, 1971; Udry, 1996; Yotopoulos and Lau, 1973). Hence, our regression can be seen as a way to examine the economic efficiency gains that farmers realize when their plots are irrigated. This economic efficiency can be thought of as a shift up of the supply curve caused by increased irrigation (everything else held constant).

To understand the effect of irrigation on agricultural performance by using Eq. (3), we adopt a three-step strategy. First, we examine the effect of irrigation on *yields for individual crops*. While interesting by itself, such a regression does not capture all of the dimensions of the effects of irrigation. In the next step, we estimate a second model to explain *agricultural revenues*. If irrigation allows farmers to cultivate two crops per year and/or if it allows shifting into cash crops that generate higher revenues per hectare, the aggregate household agricultural revenue equation will capture the higher output from irrigation. Finally, we explain yields separately for rich and poorer areas in order to gauge the differences in the effects of irrigation in rich and poor areas. Note all the dependent variables are in log form so the coefficients represent percentage changes in yields or revenues.

Multivariate results

Our analyses perform well. More than half of the regressions have R^2 statistics that exceed 0.4, levels that can be counted as high for cross-section supply regressions (Tables 4–6). Most of the coefficients in the models have the expected signs and in some cases are highly significant. For example, we find that the quality of the soil positively affects yields in most equations. Also, as expected, the plot-specific weather shock reduces yields (e.g., Table 4, rows 4 and 9).

Most importantly, the findings support the hypothesis that irrigation raises yields for most crops (Table 4). For example, irrigation increases the yields of wheat by 17.7%, those of maize by 29.4%, and those of cotton by 28.4% (row 1). The multivariate analysis results of crop-specific yields do differ from the descriptive results when examining the magnitude of the differences. With the exception of maize, the magnitude of the impact of irrigation is lower in the regression results than in the descriptive statistics. Most likely this is because in the regressions the irrigation impacts are being conditioned on the level of other variables, such as soil quality, and these other variables account for part of the irrigation effect (e.g., since most irrigated land is "good").

Table 4
The impact of irrigation on crop yield with household fixed effects

	Dependent variables: log crop yield		
	(1) Wheat	(2) Maize	(3) Cotton
Irrigation status			
Irrigated (by surface water or ground water)	0.177	0.294	0.284
	(2.81)***	(4.17)***	(5.28)***
Land characteristics			
Good soil quality	0.174	0.130	0.008
	(5.41)***	(3.50)***	(0.24)
Topography – plain	0.070	0.302	−0.001
	(0.65)	(1.38)	(0.02)
Topography – hill	0.132	0.181	0.083
	(2.53)**	(0.90)	(0.92)
Plot size	0.041	0.204	0.010
	(0.39)	(1.42)	(0.65)
Distance from home	0.003	−0.005	0.008
	(0.21)	(0.16)	(0.24)
Shock: severity of disaster[a]	−0.009	−0.016	−0.001
	(6.22)***	(12.78)***	(1.65)
Single season crop[b]	−0.040	−0.106	0.054
	(0.87)	(2.06)**	(2.43)**
Number of plots	1027	1116	141
Number of households with multiple plots	297	329	38
R^2	0.15	0.47	0.39

Absolute value of t statistics in parentheses. * significant at 10%; ** significant at 5%, *** significant at 1%.
[a] Severity of disaster means percentage reduction of production.
[b] A dummy variable that equals 1 if the crop is not grown in conjunction with other crops during the year and is 0 otherwise.

Perhaps most significantly from a methodological point of view, the estimated coefficients on irrigation using either no fixed effects or aggregate data are always lower than that obtained from the household fixed effects model (Table 5). In our analysis, we use the impact of irrigation on maize yields as an example. Under the household fixed effects model, the coefficient on the irrigation variable is positive and significant (29.4% – column 1). In contrast, when no fixed effects are used, the coefficient becomes not significantly different from zero, signaling the potential problem of omitted variables (column 2). We construct a set of county level data from our plot level data.[7] When using this aggregated data in which the variations of plot-specific factors such as soil quality are removed, the coefficient on the irrigation variable also becomes not significantly different from zero (column 3). These results demonstrate empirically the

[7] The aggregated data set is constructed by replacing all the variables with their means at the county level. When doing so, our specification has to change slightly. Instead of using dummy variables (e.g. the variable good soil quality that equals 1 when the soil quality is good and 0 otherwise) (as we do in the household-level equations), in our county-level regressions, we create a continuous variable that measures the variable in terms of proportions (e.g., the share of land in the county sample that is good).

Table 5
The impact of irrigation on maize yield under different estimating approaches

	Dependent variables: log crop yield		
	(1) With household fixed effects	(2) Without any fixed effects	(3) Using constructed aggregate data at the county level[c]
Irrigation status			
Irrigated (by surface water or ground water)	0.294	0.023	−0.150
	(4.17)***	(0.70)	(1.34)
Land characteristics			
Good soil quality	0.130	0.201	1.118
	(3.50)***	(5.64)***	(4.05)***
Topography – plain	0.302	0.256	1.124
	(1.38)	(2.77)***	(2.57)**
Topography – hill	0.181	0.219	1.035
	(0.90)	(2.41)**	(2.23)**
Plot size	0.204	−0.024	−1.275
	(1.42)	(0.24)	(2.51)**
Distance from home	−0.005	−0.048	0.031
	(0.16)	(2.11)**	(0.57)
Shock: severity of disaster[a]	−0.016	−0.013	−0.014
	(12.78)***	(21.96)***	(10.09)***
Single season crop[b]	−0.106	0.121	0.412
	(2.06)**	(3.45)***	(4.78)***
R^2	0.47	0.36	0.21

Absolute value of *t* statistics in parentheses. * significant at 10%; ** significant at 5%, *** significant at 1%.
[a] Severity of disaster means percentage reduction of production.
[b] A dummy variable that equals 1 if the crop is not grown in conjunction with other crops during the year and is 0 otherwise.
[c] Please refer to Footnote 8 for the method used to aggregate the data.

coefficient on irrigation may be biased downward either when the unobserved heterogeneity is not controlled for or when the variations in factors that may affect yield are not accounted for. This downward bias may explain the insignificant effects of irrigation on agricultural performance found in most previous studies.

The impact of irrigation becomes even greater when we look at household crop revenue (Table 6). Overall, irrigation increases revenue by 76.1% (column 1), a figure that is only slightly less than the unconditional difference observed in the descriptive statistics (Table 3, row 1). In other words, according to these results, most of the differences between revenues on irrigated and non-irrigated plots are due to the addition of irrigation and not other plot characteristics. The magnitude of the coefficient drops to 42.9% when household dummies are replaced with four household-level variables and a set of village dummies (column 2). Using village dummies instead of household dummies moves the coefficient of interest in the same direction as was observed in the yield equations when no fixed effects are used at all. Apparently, the use of village dummies and four household-level variables absorbs some, but not all, of the unobserved heterogeneity in crop revenue function.

Table 6
The impact of irrigation on household crop revenue per plot

Level of fixed effects	Dependent variable: log annual household crop revenue		
	Household	Household	Village[a]
Irrigation status			
Irrigated (by surface water or ground water)	0.761		0.429
	(15.98)***		(13.83)***
Irrigated by surface water		0.681	
		(13.23)***	
Irrigated by ground water		1.019	
		(11.70)***	
Land characteristics			
Good quality	0.286	0.281	0.219
	(7.09)***	(7.19)***	(7.83)***
Topography – plain	0.098	0.082	−0.004
	(0.94)	(0.80)	(0.07)
Topography – hill	−0.009	−0.069	−0.104
	(0.11)	(0.89)	(2.02)**
Plot size	0.095	0.053	
	(1.02)	(0.60)	
Distance from home	0.020	0.021	0.022
	(1.12)	(1.44)	(1.58)
Shock: severity of disaster[b]	−0.009	−0.008	−0.009
	(9.50)***	(8.74)***	(11.93)***
Single season crop[c]	0.755	0.736	0.716
	(26.96)***	(26.86)***	(28.48)***
Number of plots	5352	5614	5347
Number of household with multiple plots	1043	1070	
Number of villages			60
R^2	0.23	0.23	0.20

Absolute value of t statistics in parentheses. * Significant at 10%, ** significant at 5%, *** significant at 1%.
[a] In the village fixed effects model, we use four household characteristic variables that are not reported here: household size, average education level, total wealth and total household land.
[b] Severity of disaster means percentage reduction of production.
[c] A dummy variable that equals 1 if the crop is not grown in conjunction with other crops during the year and is 0 otherwise.

Decomposing revenue differences by crop illustrates differences among crops in the earnings potential that arises with irrigation (Table 7).[8] When a plot is irrigated, rising yields and the ability to shift into new crops, such as rice and cash crops,

[8] In trying to understand such a result, it would be interesting if we could estimate the effect of irrigation on switching to another crop or by going to a more intensive rotation. To do so, we could add to the specification in Eq. (3), a set of variables that interact major crops with irrigation or types of rotation with irrigation. Unfortunately, the coefficients in such an equation are likely to be subject to an endogeneity bias, because we would expect crop choices to be affected by the same (unobserved) variables that also affect revenues. Since we do not have any valid instruments to control for the endogeneity, we report the results in Appendix A and use them to check the robustness of our results.

Table 7
Decomposed impact of irrigation on household crop revenue with household fixed effects

	Dependent variable: log annual household crop revenue	
Interaction dummies		
Rice * Irrigation	1.156 (24.41)***	
Wheat * Irrigation	0.573 (10.34)***	
Maize * Irrigation	0.619 (10.85)***	
Single season rice * Irrigation	1.004 (18.36)***	
Single season wheat * Irrigation	0.206 (1.83)*	
Single season maize * Irrigation	0.912 (4.00)***	
Rice rice * Irrigation	1.473 (15.46)***	
Wheat–rice rotation * Irrigation	0.106 (1.58)	
Wheat–maize rotation * Irrigation	0.989 (12.32)***	
Wheat–other crop rotation * Irrigation	0.863 (9.02)***	
Maize-other crop rotation * Irrigation		0.832 (9.18)***
Coarse grains * Irrigation	0.317 (3.78)***	0.532 (5.67)***
Cash crops – cotton * Irrigation	1.365 (15.14)***	1.541 (14.79)***
Cash crops – peanut * Irrigation	0.887 (9.45)***	1.135 (10.78)***
Tubers * Irrigation	−1.226 (17.74)***	−1.120 (14.82)***
Land characteristics		
Good quality	0.217 (6.00)***	0.212 (5.29)***
Topography – plain	0.065 (0.69)	−0.046 (0.44)
Topography – hill	−0.027 (0.36)	−0.145 (1.68)*
Plot size	0.011 (0.12)	−0.033 (0.33)
Distance from home	0.009 (0.43)	0.028 (1.13)
Shock: severity of disaster[a]	−0.009 (10.35)***	−0.010 (9.69)***
Single season crop[b]	0.231 (6.39)***	0.400 (8.55)***
Number of plots	4858	4166
Number of households with multiple plots	978	953
R^2	0.45	0.48

Absolute value of t statistics in parentheses. * Significant at 10%, ** significant at 5%, *** significant at 1%.

[a] Severity of disaster means percentage reduction of production.

[b] A dummy variable that equals 1 if the crop is not grown in conjunction with other crops during the year and is 0 otherwise.

facilitates the largest rises in revenue (115.6% higher for rice; 136.5% for cotton; 88.7% for peanuts – column 1). Although somewhat lower, when plots are irrigated rising yields also help increase revenues on wheat (57.3%), maize (61.9%) and coarse grains (31.7%). Of all of the major crops in the sample, tubers are the only ones that do not enjoy increased revenue. Additionally, when the major grain crops, rice, wheat and maize, are disaggregated by rotation, the impact of increasing intensity also emerges (columns 2). For example, when using household fixed effects, irrigated double-cropped rice increases yields by 147.3%, higher than single season rice (100.4%). When irrigation facilitates the shift to a wheat–maize rotation, revenues generated on a plot rise by 98.9%, higher than either the rise that accompanies single season wheat (20.6%) or single season maize (91.2%).[9]

When dividing the sample into rich and poorer areas, we find similar results (Table 8). In both rich and poor areas, irrigation has a significantly positive effect on crop revenue, increasing it by 132.8% in rich areas and 43.9% in poorer ones (columns 1 and 3). While the higher marginal effects of irrigation on crop revenue in rich areas may explain why more of the past investment in irrigation has gone into favorable areas, it does not mean that the poor do not benefit. In fact, in terms of welfare effects, the poor may benefit more. Results in Table 3 show that the share of crop revenue in total income is three times as high in poor areas (34%) as in richer areas (10%). Taking this into account, irrigation benefits farmers in poorest area one and half times more that it does farmers in richer area (15% in poor areas versus 13% in richer areas). Certainly, as discussed in the descriptive analysis section, this means that irrigation also will have a positive effect on household food security of the poor.

Our results show that the magnitude of the impacts of surface water and groundwater irrigation differs in rich areas and poor areas (Table 8). In rich areas, the percentage increases in crop revenues are higher when plots are irrigated by surface water than by groundwater (column 2). Percentage increases in crop revenues of plots irrigated by surface water are also much higher in rich areas than in poor areas (column 4). Two reasons may account for the low return from surface water irrigation in poor areas. First, it could be that surface water is less reliable in poor areas. Poor areas are often located in those areas that have relatively scarce water resources. In those areas, due to the nature of the water resources, surface water is often not delivered either at the time when irrigation is required or in the quantities that are needed. Sometimes it is not delivered at all. Second, the irrigation efficiency most likely is relatively lower in poor areas. Canals in most poor areas are often not lined or the linings of canals have deteriorated over time. Under such circumstances, the benefit from using surface water, although positive, may be reduced for a given quantity of water. As a result, returns from surface water irrigation are lower in poor areas.

New irrigation projects: Benefits versus costs

Both of the descriptive statistics and the multivariate analysis have shown that irrigation raises household crop revenue per hectare. To complete our analysis of the impacts of irrigation on the welfare of rural households, a cost–benefit analysis of irrigation is conducted. In our analysis, we calculate the cost–benefit analysis by comparing the per hectare benefits of a switch from non-irrigated to irrigated cropping to the estimated per hectare costs that are associated with the new irrigation.

[9] Significantly, the wheat–rice rotation does not show any statistical difference between irrigated and non-irrigated areas. Most likely this is because in the case of only four households does a single household have both irrigated and non-irrigated plots (the requirement that needs to be met for the observations to be used).

Table 8
The impact of irrigation on crop revenue in rich and poor area in China with household fixed effects

	Dependent variables: log plot crop revenue			
	Rich area		Poor area	
	Eq. (1)	Eq. (2)	Eq. (1)	Eq. (2)
Irrigation status				
Irrigated (by surface water or ground water)	1.328		0.439	
	(14.11)***		(3.50)***	
Irrigated by surface water		1.470		0.296
		(14.30)***		(2.02)**
Irrigated by ground water		0.717		0.793
		(3.54)***		(3.55)***
Land characteristics				
Good soil quality	0.147	0.167	0.143	0.139
	(1.90)*	(2.17)**	(1.50)	(1.47)
Topography – plain	0.155	0.131	−0.327	−0.309
	(0.88)	(0.75)	(0.85)	(0.80)
Topography – hill	−0.006	0.100	−0.280	−0.277
	(0.03)	(0.53)	(1.52)	(1.51)
Plot size	0.048	0.066	−0.220	−0.236
	(0.25)	(0.34)	(1.43)	(1.54)
Distance from home	0.134	0.111	−0.302	−0.284
	(2.96)***	(2.44)**	(3.39)***	(3.18)***
Shock: severity of disaster[a]	−0.010	−0.011	−0.011	−0.011
	(4.46)***	(4.70)***	(5.99)***	(5.52)***
Single season crop[b]	0.624	0.599	1.086	1.105
	(11.54)***	(11.05)***	(13.91)***	(14.06)***
Number of plots	1542	1542	959	959
Number of households with multiple plots	309	309	172	172
R^2	0.25	0.26	0.28	0.29

Absolute value of t statistics in parentheses. * significant at 10%; ** significant at 5%, *** significant at 1%.

[a] Severity of disaster means percentage reduction of production.

[b] A dummy variable that equals 1 if the crop is not grown in conjunction with other crops during the year and is 0 otherwise.

The benefit from irrigation is measured as the increase in household annual crop revenue due to irrigation. In our regression, the coefficient on the irrigation dummy variable (either irrigated by surface water or groundwater) estimates by how much irrigating a plot increases crop revenue, holding other things constant (Table 6).

At the same time, of course, there could be increased costs. The costs associated with increasing irrigation mainly include two components. The first component is the increase in the input costs that a farmer incurs when a plot is irrigated. The most obvious added direct cost is that associated with the payment of a water fee (especially in the case of surface water) or the pumping cost (in the case of groundwater and some surface water systems). In addition, since irrigation allows the farmer to make more intense use of the land, farmers working on irrigated plot might expect to use higher levels of variable inputs, such as fertilizer, pesticide and labor.

Unfortunately, we did not collect all inputs by plots; we only collected inputs on a per household basis. To obtain estimates of the added costs associated with newly irrigated plots, we had to rely on two subsets of households from our overall sample: (a) households that only have irrigated plots; and (b) households that only have non-irrigated plots. The increase in the input costs is then measured as the difference in the total input costs between these two groups.

The second component of the additional cost of new irrigation is that associated with the cost of constructing and operating an irrigation system. For example, in the case of a new surface water irrigation system, such a cost would include the depreciation of the canal system, the expected maintenance of canal system and the opportunity cost of investment. Since this information was not collected during the 2000 CNRS, we had to rely on another set of data: the 2003 Public Investment in Rural Poverty and Development Survey. Fortunately, in this data set, there is detailed information on the amount of total investment on irrigation infrastructure and the area of land covered by the project.[10]

The results of our cost–benefit analysis show that most of the investments in irrigation have positive returns (Table 9). In a surface water irrigation system, irrigation will increase household annual crop revenue by 1587 yuan/ha (column 1). The input costs of households that use surface water irrigation increase by 449 yuan/ha on average. Depending on the type of the surface water irrigation system that is being installed, the construction and operating costs vary. In villages that only have unlined canals, the construction and operating costs may be as low as 159 yuan/ha. In other villages that have lined canals and invest in power lifting irrigation stations, the costs may be as high as 705 yuan/ha. If we take these costs as typical of those villages that have access to new irrigation projects, then, on average, in about 62% of the villages that used surface water irrigation, the benefits of adding irrigation are higher than costs. In about 52% of villages that use groundwater irrigation, the benefits are higher than the costs.

While we believe our results are fairly robust, caution should be taken in interpreting the results of our cost–benefit analysis. Specifically, due to lack of data, it is possible that some elements of the costs and benefits of irrigation have not been accounted for. For example, the environmental costs associated with irrigation are not included. Indirect benefits from increased income due to higher crop revenue (and the benefits of reduced poverty) are not included either.[11]

[10] The data used to estimate the ownership and operating costs per ha of new irrigation system were collected by the Center for Chinese Agricultural Policy, Chinese Academy of Sciences. The data come from a randomly selected, nationally representative sample of 2376 villages in six provinces of rural China (Hebei, Jilin, Jiangsu, Sichuan, Shanxi and Gansu). Six counties were selected from each province, two from each tercile of a list of counties arranged in descending order of per capita gross value of industrial output. Within each county, the survey team also chose six townships, following the same procedure as the county selection. On average, enumerators surveyed around 11 villages in each township.

[11] We also are not able to include the national and provincial irrigation investments (which are not included in local project).

Table 9
Average cost of increasing irrigated land by 1 ha (yuan/ha/year)

Type of irrigation system	Benefit	Cost associated with irrigation			Comparison
	(1) Increase in annual crop revenue	(2) Total	(3) Input costs[a]	(4) Ownership and operating costs[b]	(5) Percentage of sample villages that have positive returns from investments in irrigation
Surface water	1587[c]	608–1154	449	159–705[e]	62.3
Groundwater	2617[d]	807	672	135[f]	51.9

Source of data: Data for benefit and input costs are from 2000 China National Rural Survey; Data for operating costs and annual ownership cost are from 2003 Public Investment in Rural Poverty and Development Survey.

[a] Input costs associated with irrigation include costs on purchasing water, energy, and fertilizer, etc. Labor expenditures are also included.

[b] Ownership cost includes depreciation of the irrigation system and opportunity costs of capital. It is determined by spreading the purchase and installation cost over its expected use period. Operating costs include operation, repairs and maintenance of the equipment.

[c] The increase in the annual crop revenue is calculated using the crop revenue from non-irrigated plots (column 5, Table 3) and the percentage increase in annual household crop revenue due to surface water irrigation (column 2, row 2 Table 6).

[d] The increase in the annual crop revenue is calculated using the crop revenue from non-irrigated plots (column 5, Table 3) and the percentage increase in annual household crop revenue due to groundwater irrigation (column 2, row 3 Table 6).

[e] The component of a surface water irrigation system includes canals in most villages. In villages that use lifting irrigation, pumps and investment in power lift station (in some villages) are also included. In other villages, ponds, small weirs or dams may also be part of a surface water irrigation system. Henceforth, the component of a surface water irrigation system varies cross villages. The ownership and operating costs differ across villages correspondingly.

[f] In most villages, the component of a groundwater irrigation system includes wells, pumps, underground pipes and other equipment such as transformers.

Conclusion

In this paper, we explore the relationship between irrigation status and crop yields and crop revenues. Our paper provides evidence of irrigation's strong impact on yields and revenues, both descriptively and in the multivariate analysis. We also find that although the marginal impact of irrigation on revenue appears to be higher in richer areas, since incomes of those in poor areas rely more on cropping, farmers in poor areas increase their incomes relatively more than farmers in richer areas. In addition, using one other source of data, it appears that even after accounting for the increased capital costs and production costs, returns from investments in irrigation are positive in the majority of the villages that have invested in new irrigation system.

The strong and robust findings in our paper of the effect of irrigation on agricultural performance relative to previous studies almost surely are in part a function of our data and methods. By using plot level data, we can control for many of the plot-level factors that also affect yields as well as irrigation. By having observations from more than one plot per household, we show that when using household fixed effects (versus only controlling for part of the household and village effects or none), the effect of irrigation almost always rises. In fact, when we go from controlling no supra-plot effects to the fixed effects model, the impact of irrigation goes from insignificant (zero) to highly significant and positive. Hence, it could be that omitted variable bias and aggregate data cause the failure to find strong irrigation effects in previous studies.

If irrigation has such a great effect on agricultural performance it is no wonder why so much of the budget of many countries has gone towards irrigation in the past. Moreover, although the costs of the project must be considered, the malaise that pervades the international community in irrigation may need to be questioned (Byerlee et al., 1999). One of the implications of our work is that when evaluating the benefits of irrigation, analysts may want to give extra weight to irrigation projects because of their positive impact on food production and potential poverty reducing effects. Our findings of the effect of irrigation on the income of those in poor areas indicates the poverty alleviation programs, in particular, may want to consider increasing or at least not diminish the role of irrigation in their portfolio of activities.

Our analysis, however, does not indicate that investments should be made to increase irrigated area in all villages in all of China. As discussed in the cost–benefit analysis section, in some of the villages, costs of increasing irrigation may outweigh benefits of doing so. In addition, returns to investment in irrigation may be lower when other factors are taken into account (Jaglan and Qureshi, 1996).[12] One such factor is the negative impacts of irrigation on environment. In other cases, the expansion of irrigated area increases demand for water and may lead to depletion of the groundwater resource that is increasingly scarce. Under such circumstances, investments in irrigation might want to be put into improve irrigation efficiency by providing water saving technologies or improving the performance of irrigation infrastructure. Alternatively, other investments, such as investment in education, should be considered since these investments may have higher returns than investment in irrigation (Fan et al., 2004).

Acknowledgements

The authors would like to thank David Dawe, Richard Howitt, David Molden, Siwa Msangi, and Mark Rosegrant for comments on earlier drafts of this paper. Rozelle is a member of the Giannini Foundation. We acknowledge the financial support from the Emerging Markets Office of the Foreign Agriculture Service (US Department of Agriculture), International Water Management Institute and

[12] If we consider the returns to water projects for industrial use as the opportunity costs of investments in irrigation, marginal returns from irrigation would be lower had water been priced based on the market value. Thank one of the reviewers for pointing this out.

National Sciences Foundation of China (70021001 and 70003011) and Iowa State University.

References

Bhattarai, M., Sakthivadivel, R., Hussain, I., 2002. Irrigation impacts on income inequality and poverty alleviation: policy issues and options for improved management of irrigation systems. Working Paper No. 39, International Water Management Institute.

Byerlee, D., Heisey, P., Pingali, P., 1999. Realizing yield gains for food staples in developing countries in the early 21st century: prospects and challenges. In: Paper presented by The Vatican at Food Needs of the Developing World in the Early 21st Century, January 27–30, 1999.

China Council for International Cooperation on Environment and Development, 2004. China's agricultural and rural development in the new era: challenges, opportunities and policy options: an executive summary of policy report. China Commission International Cooperation for the Environment and Development, Agricultural and Rural Development Task Force, September 2004.

Dhawan, B.D., 1988. Irrigation in India's Agricultural Development: Productivity, Stability, Equity. Sage Publications India, New Delhi, India.

Fan, S., Hazell, P., Throat, S., 1999. Linkages between Government Spending, Growth, and Poverty in Rural India. International Food Policy Research Institute..

Fan, S., Zhang, L., Zhang, X., 2004. Reforms, investment, and poverty in rural China. Economic Development and Cultural Change 52 (2), 395–421.

Food and Agriculture Organization of the United Nations, 2002. FAO Statistical Database. Available from: <http://faostat.fao.org/faostat/collections?subset=agriculture>.

Hu, R., Huang, J., Jin, S., Rozelle, S., 2000. Assessing the contribution of research system and CG genetic materials to the total factor productivity of rice in China. Journal of Rural Development 23 (Summer), 33–79.

Huang, J., Rozelle, S., Rosegrant, M.W., 1999. China's food economy to the twenty-first century: supply, demand, and trade. Economic Development and Cultural Change 47 (4), 737–766.

Huang, J., Rozelle, S., Chang, M., 2004. Tracking distortions in agriculture: China and its accession to the World Trade Organization. The World Bank Economic Review 18 (January), 59–84.

Huang, Q., Dawe, D., Huang, J., Rozelle, S., Wang, J., 2005. Irrigation, poverty and inequality in rural China. The Australian Journal of Agricultural and Resource Economics 49 (2), 159–175.

Jaglan, M., Qureshi, M., 1996. Irrigation development and its environmental consequences in arid regions of India. Environmental Management 20 (3), 323–336.

Jin, S., Huang, J., Hu, R., Rozelle, S., 2002. The creation and spread of technology and total factor productivity in China's agriculture. American Journal of Agricultural Economics 84 (4), 916–930.

Kennedy, P., 1998. A Guide to Econometrics. The MIT Press, Cambridge, MA.

Lardy, N., 1983. Agriculture in China's Modern Economic Development. Cambridge University Press, New York.

Lau, L.J., Yotopoulos, P.A., 1971. A test for relative efficiency and application to Indian agriculture. American Economic Review 61 (1), 94–109.

Liao, Y., 2003. Irrigation water balance and food security in China. Ph.D. Dissertation, The Chinese Academy of Agricultural Science.

Ministry of Water Resource, 2001. China Water Resource Yearbook. China Water-Hydropower Publishing House, Beijing.

National Statistical Bureau of China, 2001a. China's Rural Poverty Monitoring Report: 2001. China Statistics Press, Beijing, China.

National Statistical Bureau of China, 2001b. Statistics Yearbook of China. China Statistics Press, Beijing, China.

Park, A., Wang, S., 2001. China's poverty statistics. China Economic Review 12, 384–398.

Putterman, L., 1993. Continuity and Change in China's Rural Development: Collective and Reform Eras in Perspective. Oxford University Press, New York.

Rosegrant, M., Evenson, R., 1992. Agricultural productivity and sources of growth in South Asia. American Journal of Agricultural Economics 74 (August), 757–761.
Rosegrant, M., Kasryno, F., 1994. Dynamic supply reponse for Indonesian food crops. Working Paper, International Food Policy Research Institute.
Roy, A.D., Shah, T., 2003. In: Llamas, M.R., Custodio, E. (Eds.), Socio-ecology of Groundwater Irrigation in India. Swets & Zeitlinger Publishers, Netherlands.
Rozelle, S., 1996. Stagnation without equity: patterns of growth and inequality in China's rural economy. The China Journal 35, 63–92.
Travers, L., Ma, J., 1994. Agricultural productivity and rural poverty in China. China Economic Review 5 (1), 141–159.
Udry, C., 1996. Gender, agricultural production, and the theory of the household. Journal of Political Economy 104 (5), 1010–1046.
World Bank, 2001a. China: Overcoming Rural Poverty. World Bank, Washington, DC.
World Bank, 2001b. Poverty Trends and Voices of the Poor. World Bank, Washington, DC.
Yotopoulos, P.A., Lau, L.J., 1973. A test for relative economic efficiency: some further results. American Economic Review 63 (1), 214–223.
Zhu, J., 2004. Public Investment and China's long-term food security under WTO. Food Policy 29, 99–111.