Thailand Vietnam Socio Economic Panel

Does irrigation development mitigate weather extremes' impacts and reduce poverty? Evidence from rural Southeast Asia

Manh Hung Do, Trung Thanh Nguyen

Leibniz Universität Hannover

2023

TVSEP Working Paper

WP-034

Gefördert durch DFG Deutsche Forschungsgemeinschaft

Leibniz Universität Hannover

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Thailand Vietnam Socio Economic Panel (TVSEP)
TVSEP Database Centre
Leibniz Universität Hannover
Königsworther Platz 1
30167 Hannover, Germany

Contact: thanh.nguyen@iuw.uni-hannover.de

Does irrigation development mitigate weather extremes' impacts and reduce poverty? Evidence from rural Southeast Asia

Manh Hung Do[1], Trung Thanh Nguyen[1, *]

Abstract

Water is critical for agriculture in developing countries and climate change has created extreme weather events that push farmers into poverty. In this study, we first examine the role of year-round irrigation at village level in ensuring irrigation at household level and helping farmers to cope with weather shocks. We then investigate the effects of irrigation on crop farming efficiency, income, and poverty of rural households. We use a panel dataset of 1,681 households in Thailand and 1,699 households in Vietnam collected in 2010, 2013, and 2016 with a total number of 10,140 observations. Our results show that the availability of year-round irrigation at village level positively and significantly increases the share of irrigated land areas at household level. Besides, weather shocks significantly decrease crop farming efficiency and an improvement in irrigation has a positive effect on farming efficiency. Further, an increase in irrigated land share at household level increases crop income and total household income, and decreases poverty. Our results suggest that making irrigation water available throughout the year is needed for farmers to cope with extreme weather events and to escape from poverty. This should be done by developing infrastructure for ensuring year-round irrigation.

Keywords: Thailand, Vietnam, Irrigation, Multidimensional poverty, Instrumental variable

JEL: Q57, Q12, R20

RePEc:tvs:wpaper:wp-034

This study relies on data from the long-term project No. 20220831434900116103, funded by the Deutsche Forschungsgemeinschaft (DFG). For more detailed information, see www.tvsep.de. We highly appreciate the effort of our colleagues at the Leibniz University Hannover for data collection and cleaning. MH Do would like to thank the German Academic Exchange Service (DAAD) for financial assistance.

[1] Institute for Environmental Economics and World Trade, Leibniz Universität Hannover, Germany

[*] Corresponding author, Tel: +49 511762 4827, Fax: +49 511762 2667, Email: thanh.nguyen@iuw.uni-hannover.de, postal address: Koenigsworther Platz 1, 30167 Hannover, Germany

1. Introduction

Water is essential for life and underpins socio-economic development. Managing water resources is becoming increasingly critical in emerging economies in Asia such as Thailand and Vietnam, which have rapid economic and population growth, but also face with a changing climate. In these countries, although the contribution of the agricultural sector to the gross domestic product (GDP) has been decreasing, the sector is still very important. In a recent Asian development outlook, the Asia Development Bank (ADB) points out that agriculture employs more than 40% of the population in South Asia (ADB, 2020a). However, agriculture is also known as one of the largest water consumers, for example, it uses about 80% of Asia's freshwater (ADB, 2020a). It is widely known that water is becoming scarcer and thus using water more efficiently is essentially needed. Addressing this challenge is even more difficult in the context of climate change (Balasubramanya et al., 2022; Tortajada and Biswas, 2022). Extreme weather events such as droughts and floods seem to be more frequent and severe due to climate change (Nguyen et al., 2020). As agriculture is a weather sensitive sector, these events not only pose a threat to sustainable water management (Aryal et al., 2021; Kim et al., 2019; McNamara et al., 2021), but also destroy crop and livestock production (Nguyen, Nguyen, Do et al., 2022). As a consequence, it negatively affects global food security.

Irrigation has been found to be significant for improving agricultural productivity and crop income, ensuring food security, and eradicating poverty (Dillon, 2011; Huang et al., 2006; Hussain, 2007; Kandulu & Connor, 2017; Lipton et al., 2003; Senaratna Sellamuttu et al., 20 Smith, 2004; Tesfaye et al., 2008; Tortajada, 2014). It also helps farmers cope with weather shocks induced by climate change (Marie et al., 2020). Therefore, investing in irrigation is important and has been a priority of many governments in the Global South (Muller et al., 2015; Tortajada et al., 2022). However, the focus is mainly on making access to water for irrigation available to farmers. Evidence on the role of year-round irrigation in coping with extreme weather events is rare. Furthermore, studies on the impact of irrigation have paid more attention to partial productivity measures (e.g., crop output or revenue per hectare) (Dillon, 2011; Huang et al., 2006; Hussain, 2007; Kandulu & Connor, 2017; Smith, 2004), while evidence on the effect of irrigation on farming technical efficiency is much less studied.

Against this background, this study aims to fill the above research gaps by answering the following research questions (i) Does year-round irrigation at village level play a significant role in increasing irrigated land area at household level in the context of weather shocks? (ii)

What are the effects of irrigation on farming efficiency? and (iii) How does irrigation affect households' income and poverty? We contribute to the literature by providing empirical evidence on the role of year-round irrigation at village level for rural households to cope with weather shocks and on the effects of irrigation at household level on crop farming efficiency, income, and poverty. The evidence is vital for stimulating policies and investments regarding the development of irrigation at local levels. Our hypotheses are that year-round irrigation at village has a positive and significant association with household's irrigation and that better irrigation has a positive and significant effect on crop farming efficiency, income, and poverty reduction. We use a panel dataset and employ a fixed-effects with instrumental variable (IV) approach to address the problems of unobserved heterogeneity and endogeneity in impact assessment.

We focus on Thailand and Vietnam because of the following reasons. First, they are among the most affected countries by climate change (Eckstein et al., 2020; Nguyen & Nguyen, 2020). Second, they belong to the Southeast Asian region where the demand for water in agriculture is relatively high (ADB, 2020a). Third, they are emerging economies experiencing rapid economic growth, but the large majority of their population are living in rural areas and engaging in agricultural production (Nguyen et al., 2021). Within these countries, the Northeast of Thailand and the Central of Vietnam are characterized by high dependency on agriculture (and crop production in particular), high exposure to weather shocks, and low development of agricultural infrastructure (Hardeweg et al., 2013; Nguyen et al., 2020; Poggi, 2019; Suebpongsang et al., 2020). Last, poverty rates in these countries are decreasing but are still high at more than 6% at the national poverty lines (World Bank, 2022). Our study is thus expected to provide useful implications for policy makers in developing countries to formulate policy responses for enhancing irrigation development to improve production efficiency, increase income, and reduce poverty.

2. Literature review

Extreme weather events such as droughts and floods seem to be more frequent and severe due to climate change (Hamududu & Ngoma, 2020; Kaini et al., 2021). They negatively affect rural households' income from farm and non-farm sources and further push these households into poverty (Nguyen et al., 2020). Thus, the availability of year-round irrigation provides rural households with an access to water for agricultural production and mitigates the impacts of these extreme weather events. Access to irrigation is key for rural households to improve their livelihood strategies (Ashley & Carney, 1999; Blakeslee et al., 2023; Nguyen et al., 2017; Senaratna Sellamuttu et al., 2014).

Irrigation has been found to be significant for improving agricultural productivity and crop income, ensuring food security, and eradicating poverty (Blakeslee et al., 2023; Dillon, 2011; Huang et al., 2006; Hussain, 2007; Kandulu & Connor, 2017; Smith, 2004; Tesfaye et al., 2008). Besides, irrigation provides employment opportunities for surplus labor (Hussain & Hanjra, 2004) and helps farmers cope with weather shocks caused by climate change (Marie et al., 2020). Among these effects, the nexus between irrigation, agricultural production, and poverty have been widely studied because of its diverse effects on the poor (Lipton et al., 2003). The development of irrigation can bring substantial benefits to rural regions by raising agricultural productivity and increasing the wealth of rural villages (Blakeslee et al., 2023).

Although the literature related to irrigation is rich, there are still some important research gaps. First, evidence on the role of year-round irrigation in coping with extreme weather events is vital for stimulating policies and investments regarding the development of irrigation system at local levels. Climate-driven changes in precipitation and drought patterns have an effect on the availability of water and cause water scarcity (Kaini et al., 2021; Malek et al., 2018). Furthermore, the demand for higher agricultural productivity leads to an increasing demand for water and growing conflicts among water users (Lenton, 1994). This leads to an implication that investments in irrigation development to just provide access to irrigation are not enough, but these investments should also ensure the availability of water throughout the year under the context of adverse weather shocks. However, evidence on the role of year-round irrigation in coping with extreme weather events is rare.

Second, studies on the impact of irrigation have paid more attention to partial productivity measures (e.g., output per hectare) and crop revenue, while empirical evidence on the effect of irrigation on farming technical efficiency is rather scarce (Huang et al., 2006; Hussain & Hanjra, 2004; Mdemu et al., 2017). At farm level, better irrigation may result in better yields, but it may also be accompanied by increased costs (Ho et al., 2022; Huang et al., 2006). Thus, to what extent an improvement in irrigation leads to an increase of crop farming efficiency is an important question that needs to be answered.

Third, evidence on the effects of irrigation on poverty appears to be mixed. On the one hand, some studies find that irrigation helps increase income and reduce poverty (Dillon, 2011; Huang et al., 2006; Kandulu & Connor, 2017). On the other hand, it has been found that rural households have still been trapped into poverty, even though they have access to irrigation (Senaratna Sellamuttu et al., 2014), or there are possible negative impacts on the poor caused by irrigation (Lipton et al., 2003). Moreover, most of the studies on the association between irrigation and poverty rely on income data to measure poverty. This income-based poverty measure has many disadvantages (Smith, 2004; World Bank, 2020).

Last, some of the previous studies on the impact of irrigation on poverty employed cross-sectional data or research methodologies that cannot address the problems of unobserved heterogeneity and endogeneity. The use of cross-sectional data might not well reflect the impact of irrigation because investments in irrigation are long-term (Lenton, 1994). The adoption of irrigation at household level is apparently endogenous (Koundouri et al., 2006; Parry et al., 2020). Consequently, studies that do not address the endogenous aspect of irrigation might culminate in biased results.

3. Study sites and data description

3.1 Study sites and sample

We use the data from the "*Thailand - Vietnam Socio-Economic Panel (TVSEP): Poverty dynamics and sustainable development*" funded by the German Research Foundation (see www.tvsep.de for more information). The objective of this project is to provide a better understanding of socio-economic development and vulnerability to poverty dynamics in the rural areas of these two emerging economies (Hardeweg et al., 2013). The sampling procedure for data collection is based on the guidelines of the Department of Economic and Social Affairs of the United Nations (UN, 2005) and includes the following steps. First, three provinces in Northeast Thailand (Ubon Ratchathani, Nakhon Phanom, and Buriram) and three provinces in Central Vietnam (Ha Tinh, Thua Thien Hue, and Dak Lak) were selected as the TVSEP's study sites (Figure 1). These three provinces were chosen based on their high reliance on agriculture, a low average per capita income, and poor infrastructure. Second, sampled communes in these provinces were selected based on the population share. Third, two villages per commune were sampled proportionally to the size of the population in the commune. Last, a fixed sample of ten households from each sampled village was randomly selected with equal probability selection. This procedure resulted in a sample of 440 villages and 4,400 households in these two countries.

Figure 1. Study sites of the TVSEP project in Thailand and Vietnam (source: Nguyen et al. (2020))

The TVSEP project uses two survey instruments to collect information at household and village levels, namely a structured household questionnaire and a structured village questionnaire. The household questionnaire includes a wide range of information such as household demographic characteristics (e.g., age, education, employment, and health status), household's income and livelihood strategies (e.g., crop and livestock production, natural resource extraction, wage-employment, and self-employment), household's consumption, household's assets, and shock experience. The reference period is normally from May of the previous year to April of the survey year. For each sampled household, the household head was interviewed. The village questionnaire captures the information at village level such as irrigation (if year-round irrigation is available, and the water sources of year-round irrigation), infrastructure (such as road quality), and the distances from the villages to the closest markets, to district centers, and to provincial centers (see Table A1 in the supplemental data for definition and measurement of variables at household and village levels). For each sampled village, the village head was interviewed.

In this study, we use a balanced panel dataset of 3,380 households (1,681 from Thailand and 1,699 from Vietnam) from 440 villages surveyed in three years (2010, 2013, and 2016) since they provide an equal time gap between the survey waves and have adequate data at village level. Hence, the final sample includes 10,140 observations from two countries for the years of 2010, 2013, and 2016.

Besides the TVSEP data, we employ the precipitation data from the Tropical Rainfall Measuring Mission (TRMM). This is a joint mission of the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). The precipitation data from TRMM is spatial with a 0.25° × 0.25° resolution and temporal with daily and 3-hourly records (see Kummerow et al. (1998) for the TRMM sensors and data algorithms). However, the data are only available for the period from 1998 to 2014.

3.2 Data description

Table 1 presents the descriptive summary of household and village characteristics. Panel A of this table shows the households' demographic characteristics. In 2010, 28% and 40% of the households report experiencing at least a weather shock (either a flood, a drought, a landslide, or a storm) in Thailand and Vietnam, respectively. This share shows an increasing trend in Thailand when it rises to 33% in 2016. In Vietnam, the exposure to weather shocks drops to 18% in 2013, but it increases again to 23% in 2016. The average age of household heads in our sample is about 56 years old. In both countries, most of the households are male-headed. However, the number of households with male heads is decreasing in both countries. The Thai majority in Thailand and the Kinh majority in Vietnam are predominant in our sample when they account for 94% and 78% of the sample in Thailand and Vietnam, respectively. The average number of household members is about four, but it shows a decreasing trend in both countries over time. The share of laborers increases from about 70% in 2010 to 80% in 2016.

Panel B in Table 1 presents the household's assets and production. Thai households have a relatively higher asset value per capita than Vietnamese households. The asset value per capita of rural households in Thailand increases from PPP$ 1,680 in 2010 to PPP$ 2,700 in 2016, while that of rural households in Vietnam rises from PPP$ 590 in 2010 to PPP$ 951 in 2016. The difference in asset values is statistically significant between two countries over time. Overall, Thai households have more phones and tractors, while Vietnamese households own more sprayers and pumps. Rural households in Thailand have a larger land size per capita at 1.0 hectare (ha) per person, while this number is only 0.3 ha in Vietnam.

Table 1. Descriptive summary of household and village characteristics

	Whole sample (n = 10140)	2010		2013		2016	
		Thailand (n = 1681)	Vietnam (n = 1699)	Thailand (n = 1681)	Vietnam (n = 1699)	Thailand (n = 1681)	Vietnam (n = 1699)
A. Household's demographic characteristics							
Exposure to weather shocks (yes = 1)	0.28	0.28	0.40$^{***, b}$	0.27	0.18$^{***, b}$	0.33	0.23$^{***, b}$
	(0.45)	(0.45)	(0.49)	(0.45)	(0.38)	(0.47)	(0.42)
Age of household head (years)	56.04	57.25	50.21$^{***, a}$	59.34	53.19$^{***, a}$	61.06	55.27$^{***, a}$
	(12.90)	(12.35)	(12.84)	(12.16)	(12.77)	(11.63)	(12.46)
Gender of head (male = 1)	0.77	0.74	0.85$^{***, b}$	0.71	0.83$^{***, b}$	0.68	0.80$^{***, b}$
	(0.42)	(0.44)	(0.35)	(0.45)	(0.38)	(0.47)	(0.40)
Thai (Thailand) or Kinh majority (Vietnam) (yes = 1)	0.86	0.94	0.78$^{***, b}$	0.93	0.78$^{***, b}$	0.94	0.78$^{***, b}$
	(0.35)	(0.24)	(0.41)	(0.25)	(0.42)	(0.24)	(0.41)
Household size (persons)	4.02	4.14	4.34$^{***, a}$	3.99	4.06^{a}	3.75	3.82^{a}
	(1.70)	(1.73)	(1.73)	(1.70)	(1.72)	(1.63)	(1.64)
Share of laborers (%)	74.94	70.84	70.64^{a}	72.03	74.10$^{***, a}$	83.09	78.98$^{***, a}$
	(23.02)	(22.35)	(23.15)	(22.73)	(23.13)	(22.00)	(21.96)
Schooling years of household head (years)	5.87	4.77	6.89$^{***, a}$	4.81	6.87$^{***, a}$	5.12	6.72$^{***, a}$
	(3.48)	(2.50)	(3.92)	(2.63)	(3.92)	(2.75)	(3.93)
Mean schooling years of adult members (years)	5.69	6.26	6.14^{a}	5.83	5.33$^{***, a}$	5.41	5.19$^{**, a}$
	(2.66)	(2.14)	(2.78)	(2.39)	(2.84)	(2.67)	(2.90)
B. Household's assets and production characteristics							
Asset value per capita (2005 PPP$)	1531.67	1680.14	590.92$^{***, a}$	2415.42	871.73$^{***, a}$	2704.16	951.03$^{***, a}$
	(3338.55)	(3392.79)	(760.80)	(5070.30)	(1359.89)	(4627.48)	(1516.56)
Number of phones	1.67	1.83	1.03$^{***, a}$	2.10	1.98$^{**, a}$	1.29	1.77$^{***, a}$
	(1.31)	(1.28)	(1.12)	(1.41)	(1.47)	(1.11)	(1.10)
Number of tractors	0.46	0.59	0.36$^{***, a}$	0.59	0.42$^{***, a}$	0.57	0.23$^{***, a}$
	(0.60)	(0.61)	(0.52)	(0.63)	(0.60)	(0.64)	(0.46)
Number of sprayers	0.53	0.26	0.58$^{***, a}$	0.41	0.61$^{***, a}$	0.58	0.72$^{***, a}$
	(0.71)	(0.58)	(0.54)	(0.85)	(0.64)	(0.83)	(0.63)
Number of pumps	0.64	0.48	0.71$^{***, a}$	0.44	0.74$^{***, a}$	0.58	0.87$^{***, a}$
	(0.74)	(0.73)	(0.66)	(0.68)	(0.70)	(0.77)	(0.80)
Household land per capita (ha)	0.65	0.99	0.25$^{***, a}$	1.13	0.31$^{***, a}$	0.86	0.35$^{***, a}$
	(1.04)	(1.18)	(0.71)	(1.42)	(0.65)	(1.04)	(0.55)
C. Village's characteristics							
Year-round irrigation (yes = 1)	0.58	0.32	0.65$^{***, b}$	0.60	0.67$^{***, b}$	0.63	0.60^{b}
	(0.49)	(0.47)	(0.48)	(0.49)	(0.47)	(0.48)	(0.49)
Year-round irrigation with reservoir (yes = 1)	0.20	0.09	0.15$^{***, b}$	0.30	0.19$^{***, b}$	0.29	0.18$^{***, b}$
	(0.40)	(0.28)	(0.35)	(0.46)	(0.39)	(0.45)	(0.39)
Year-round irrigation with dam (yes = 1)	0.14	0.04	0.26$^{***, b}$	0.06	0.21$^{***, b}$	0.06	0.22$^{***, b}$
	(0.35)	(0.19)	(0.44)	(0.23)	(0.41)	(0.23)	(0.41)
Having made roads instead of dirt roads (yes = 1)	0.83	0.89	0.67$^{***, b}$	0.97	0.64$^{***, b}$	0.96	0.89$^{***, b}$
	(0.37)	(0.32)	(0.47)	(0.18)	(0.48)	(0.20)	(0.31)
Share of households with cable internet at home (%)	4.44	1.92	1.91$^{***, a}$	3.46	4.91$^{***, a}$	4.05	10.36$^{***, a}$
	(9.46)	(5.02)	(6.02)	(10.23)	(7.86)	(7.13)	(14.43)
Distance to provincial capital (km)	48.97	57.46	41.35$^{***, a}$	56.50	38.96$^{***, a}$	61.19	38.65$^{***, a}$
	(30.47)	(30.40)	(26.46)	(30.35)	(26.10)	(33.89)	(25.67)
Distance to the closest market (km)	5.96	8.95	2.98$^{***, a}$	8.97	2.98$^{***, a}$	8.98	3.00$^{***, a}$
	(6.93)	(7.87)	(4.40)	(7.85)	(4.40)	(7.34)	(4.41)

Notes: Standard deviations in parentheses; ^{a}: Two-sample t-test; ^{b}: Non-parametric two-sample Wilcoxon rank-sum test; *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 2. Descriptive summary of household's crop production

	Whole	2010	2013	2016

	sample (n = 10140)	Thailand (n = 1681)	Vietnam (n = 1699)	Thailand (n = 1681)	Vietnam (n = 1699)	Thailand (n = 1681)	Vietnam (n = 1699)
A. Household's irrigation							
Share of irrigated land area in total land area (%)	55.56	26.03	$70.60^{***, a}$	49.83	$79.46^{***, a}$	30.13	$76.65^{***, a}$
	(40.51)	(38.23)	(37.38)	(33.20)	(28.90)	(34.50)	(32.75)
B. Crop's output and inputs							
Output values (2005 PPP$/ha)	2459.56	1278.77	$3581.49^{***, a}$	1577.54	$2766.06^{***, a}$	1479.70	$4041.59^{***, a}$
	(8234.31)	(3899.80)	(13172.40)	(4448.71)	(5451.45)	(5085.83)	(11595.59)
Farming area (ha)	1.62	2.70	$0.76^{***, a}$	2.44	$0.86^{***, a}$	2.19	$0.80^{***, a}$
	(4.74)	(10.51)	(1.36)	(2.64)	(2.05)	(2.48)	(1.43)
Land preparation costs (2005 PPP$/ha)	117.72	99.55	$147.82^{**, a}$	124.92	96.44^{a}	106.07	$131.30^{*, a}$
	(537.22)	(286.78)	(838.66)	(657.67)	(411.98)	(528.55)	(249.85)
Seedling costs (2005 PPP$/ha)	149.97	107.62	$169.05^{*, a}$	119.96	135.87^{a}	92.55	$273.42^{***, a}$
	(839.74)	(1203.38)	(791.85)	(833.73)	(343.39)	(539.43)	(1017.60)
Weeding costs (2005 PPP$/ha)	17.41	1.69	$15.93^{***, a}$	40.71	$21.49^{***, a}$	3.43	$21.12^{***, a}$
	(115.07)	(13.72)	(145.63)	(166.66)	(138.00)	(36.67)	(93.84)
Fertilizer costs (2005 PPP$/ha)	472.10	259.92	$699.39^{***, a}$	310.52	$715.15^{***, a}$	185.40	$655.21^{***, a}$
	(1203.09)	(1204.77)	(1018.43)	(1410.80)	(1646.90)	(245.50)	(1064.04)
Pesticide costs (2005 PPP$/ha)	65.67	21.56	$94.67^{***, a}$	31.97	$105.65^{***, a}$	21.34	$117.56^{***, a}$
	(262.02)	(96.63)	(250.61)	(492.57)	(214.91)	(67.62)	(192.41)
Harvesting costs (2005 PPP$/ha)	130.48	101.07	$119.15^{**, a}$	142.83	128.28^{a}	135.45	$155.96^{**, a}$
	(290.54)	(206.18)	(274.11)	(296.73)	(386.15)	(205.85)	(326.93)
Irrigation costs (2005 PPP$/ha)	58.98	19.00	$85.37^{***, a}$	35.22	$102.59^{***, a}$	10.27	$100.26^{***, a}$
	(467.00)	(159.02)	(246.20)	(1032.45)	(275.87)	(94.49)	(261.19)
Other costs (2005 PPP$/ha)	50.05	18.61	$32.05^{**, a}$	1.10	$36.12^{***, a}$	27.87	$183.47^{***, a}$
	(655.16)	(253.12)	(105.15)	(32.40)	(270.41)	(492.46)	(1467.06)
Farming laborers (persons)	1.98	2.08	$1.99^{**, a}$	2.01	$1.92^{**, a}$	1.89	$1.97^{**, a}$
	(1.13)	(1.10)	(1.17)	(1.13)	(1.13)	(1.14)	(1.10)

Notes: Standard deviations in parentheses; ^{a}: Two-sample t-test; $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

Panel C of Table 1 depicts the village characteristics. The improvement of year-round irrigation can be observed in Thailand when the availability of year-round irrigation increases from 32% in 2010 to more than 60% in 2016. The reason for this increase is because, since 2013, water irrigation schemes have been developed to supply irrigation water for agricultural land in this region (Kopolrat et al., 2020). On the other hand, the availability of year-round irrigation in Vietnamese villages is about 65% and 60% in 2010 and 2016, respectively. In particular, the year-round irrigation with reservoirs as the major source of irrigation water shows a dramatic improvement in Thailand and a slight increase in Vietnam. The year-round irrigation with dams as the major source of irrigation water remains unchanged in Thailand and has a modest decrease in Vietnam. Besides irrigation-related infrastructure, infrastructure for transportation and information and communication technology (ICT) has been significantly improved in Vietnam, especially after 2013. In details, villages having made roads instead of dirt roads increase from 67% in 2010 to 89% in 2016, and the share of households with cable internet at home rises from 1.91% in 2010 to 10.36% in 2016 in Vietnam. In Thailand, the figures are significantly higher for better quality roads, but lower for the share of households with cable internet at home.

Table 2 presents the descriptive summary of household's crop production. Panel A of this table shows that rural households in Vietnam have a higher share of irrigated land area (more than 70%) than that in Thailand (about 30%). Panel B depicts the output and input use for crop production. Vietnamese households have a higher crop output than Thai households do. The values of crop output per ha increase from PPP$ 3,581 in 2010 to PPP$ 4,000 in 2016 in Vietnam, and from PPP$ 1,280 in 2010 to PPP$ 1,480 in 2016 in Thailand. The difference in crop output between two countries is statistically significant. The average farming area and number of farming laborers are higher in Thailand, but Thai households spend less on the other inputs. This implies a more intensive farming practice in Vietnam. In 2010, the costs for irrigation are about PPP$ 19 per hectare and PPP$ 85.37 per hectare in Thailand and Vietnam, respectively.

4. Methodology

In this section, we explain our empirical strategies to examine the correlation of village's year-round irrigation with household's irrigated land area in the context of weather shocks (Sub-section 4.1), to estimate farming efficiency of crop production and to investigate the effects of irrigation on farming efficiency (Sub-section 4.2), to measure poverty (Sub-section 4.3), and to evaluate the impacts of irrigation on income and poverty (Sub-section 4.4).

4.1 Identifying the role of year-round irrigation at village level on irrigation of rural households

In the first step, we start with the explanation on how we examine the role of year-round irrigation in defining the irrigation of rural households. We employ a fixed-effects estimation model to account for unobservable (time invariant) characteristics of households, which can be specified as follows:

$$\boldsymbol{I_{it}} = \beta_0 + \beta_1 \boldsymbol{S_{it}} + \beta_2 \boldsymbol{YI_{jt}} + \beta_3 \boldsymbol{H_{it}} + \beta_4 \boldsymbol{V_{jt}} + \varepsilon_{ijt} \qquad (1)$$

In Equation (1), $\boldsymbol{I_{it}}$ is share of irrigated land area in total land area of household *i* at time *t*. $\boldsymbol{S_{it}}$ is a dummy variable representing the exposure to weather shocks (e.g., floods, droughts, landslides and erosion, and storms in the last 12 months of the reference period). $\boldsymbol{YI_{jt}}$ is a dummy variable representing either (i) available year-round irrigation at village level; or (ii) year-round irrigation with reservoirs as the major source of irrigation; or (iii) year-round irrigation with dams as the major source of irrigation. $\boldsymbol{H_{it}}$ is a vector of household variables (including age, gender, education level and ethnicity of household heads, household size, share of laborers, and mean education of adult members, asset value per capita, number of phones, number of tractors, number of sprayers, number of pumps, and land area per capita). $\boldsymbol{V_{jt}}$ is a vector of variables at village level (including having made-roads instead of dirt roads, share of households with cable internet at home, distance to the provincial capital, and distance to the closest market). ε_{ijt} is the error term.

To examine the coping-against-shock role of year-round irrigation, we include an interaction term between $\boldsymbol{S_{it}}$ and $\boldsymbol{YI_{jt}}$ in Equation (1) as:

$$\boldsymbol{I_{it}} = \beta_0 + \beta_1\boldsymbol{S_{it}} + \beta_2\boldsymbol{YI_{jt}} + \gamma\boldsymbol{S_{it}} * \boldsymbol{YI_{jt}} + \beta_3\boldsymbol{H_{it}} + \beta_4\boldsymbol{V_{jt}} + \varepsilon_{ijt} \tag{2}$$

In Equation (2), a positive and significant coefficient of this interaction (γ) implies that the year-round irrigation at village level helps increase the irrigation at household level when households experience weather shocks. We check for the potential problem of multicollinearity among independent variables in Equation (1) using variance inflation factor (VIF) values. The results of VIF values stacked in the first column of Table A2 in the supplemental data show no signs of this problem. We cluster our estimations at village level to have robust standard errors and to prevent auto-correlation.

4.2 Examining the effects of irrigation on crop production

In the next step, we investigate the effect of irrigation on farming efficiency. First, we estimate farming efficiency using a translog form of crop production function due to its inherent advantages compared to other functional forms such as the Cobb-Douglas production function (Chamberlin & Ricker-Gilbert, 2016; Nguyen et al., 2021). Since farmers in rural areas often operate in uncertain environments and are frequently exposed to a wide range of production risks, the stochastic frontier method (SFM) appears to be more suitable for estimating farming efficiency. We employ the time-variant stochastic frontier model which can differentiate between the inefficiency component and unobserved heterogeneity suggested by Greene (2005) with the true random-effects specification as follows:

$$\boldsymbol{O_{it}} = \alpha + \omega_i + f(\boldsymbol{X_{it}}; \vartheta) - u_{it} + v_{it} \tag{3}$$

In Equation (3), $\boldsymbol{O_{it}}$ is the output of farming of household i in time t, $f(\boldsymbol{X_{it}}; \vartheta)$ reflects the production technology of each household consisting of input vectors $\boldsymbol{X_{it}}$ and their associated vectors ϑ), u_{it} denotes the time-varying inefficiency term $(u_{it} \sim N^{+}(0, \delta_{it}^{2}) = N^{+}(0, \exp{(\omega_{u0} + Z'_{u,it}\omega_{u})}$, v_{it} represents the random two-sided noise term $((v_{it} \sim N^{+}(0, \delta_{v}^{2}))$, and ω_{i} $(\omega_{it} \sim N^{+}(0, \delta_{\omega}^{2}))$ is the specific random term that has a time-invariant characteristic and can capture the specific heterogeneity. ω_{i} has a characteristic of an *i.i.d (independent and identically distributed)* normal distribution (Abdulai & Tietje, 2007). We follow the translog specification from Nguyen et al. (2021) to estimate farm efficiency as:

$$ln\, \boldsymbol{O_{it}} = \alpha + \omega_{i} + \sum_{m} \vartheta_{m}\, ln\boldsymbol{X_{itm}} + \frac{1}{2}\sum_{m}\sum_{n} \vartheta_{mn}\, ln\boldsymbol{X_{itm}} ln\boldsymbol{X_{itn}} - u_{it} + v_{it} \qquad (4)$$

In Equation (4), $ln\, \boldsymbol{O_{it}}$ is the output values (2005 PPP$ per ha) of household *i* at time *t* in natural logarithm; $ln\boldsymbol{X_{it}}$ is the vector of inputs of household *i* at time *t* in natural logarithm, namely farming area, land preparation costs, seedling costs, weeding costs, fertilizer costs, pesticide costs, harvest costs, irrigation costs, other costs, and family farming laborers (all cost indicators are in PPP$ adjusted to 2005 prices). Furthermore, we use the correlated random-effects (CRE) model suggested by Mundlak (1978) to address the potential problem of endogeneity caused by omitted variables (e.g., farms' unobserved characteristics such as soil quality, climate conditions, and other ecological indicators) (Gautam & Ahmed, 2019). We normalize all input variables in Equation (4) by generating $\ln(X_{itm}^{*}) = \ln{(\frac{\boldsymbol{X_{itm}}}{\bar{x}_{m}})}$ before estimating the model to allow us to interpret the estimated coefficients as elasticities at means (Holtkamp & Brümmer, 2017; Nguyen et al., 2021). We employ the maximum likelihood method suggested by Belotti et al. (2013) to estimate the true random-effects SFM and to predict the farming efficiency (TE) of household *i* at time *t* as:

$$\boldsymbol{TE_{it}} = \mathrm{E}[\exp(-u_{it})\, |(v_{it} - u_{it})] \qquad (5)$$

Then, the predicted efficiency scores from Equation (5) are included as the dependent variable of a fixed-effects model to examine the effect of irrigation on farming efficiency as follows:

$$\boldsymbol{TE_{it}} = \varphi_{0} + \varphi_{1}\boldsymbol{I_{it}} + \varphi_{2}\boldsymbol{S_{it}} + \varphi_{3}\boldsymbol{H_{it}} + \varphi_{4}\boldsymbol{V_{jt}} + \epsilon_{ijt} \qquad (6)$$

In Equation (6), $\boldsymbol{TE_{it}}$ is the farming efficiency of household *i* at time *t*. $\boldsymbol{I_{it}}$ is the share of irrigated land area in total land area. $\boldsymbol{S_{it}}$ is the dummy variable of exposure to weather shocks. $\boldsymbol{H_{it}}$ and $\boldsymbol{V_{jt}}$ are household and village variables as in Equation (1), respectively. ϵ_{ijt} is the error term.

There are two concerns regarding the irrigation variable ($\boldsymbol{I_{it}}$) in Equation (6). First, we cannot justify if the reported share of irrigated land area is before or after the crop production season. To account for this issue, we include an additional estimation with a dummy variable of improved share of irrigated land area from the previous period (if the share of irrigated land area in this year is higher than the share of irrigated land area in the previous year = 1; otherwise = 0). Second, $\boldsymbol{I_{it}}$ appears to be endogenous in Equation (6). We address this problem by using a fixed-effects estimation with an instrumental variable (IV). We construct an IV relied on the TRMM precipitation data. We follow Jones and Hulme (1996) to calculate the Standardized Rainfall Anomaly Index (SRAI) for each village in a year. Since this dataset is available for the period between 1998 and 2014, the SRAI is generated from the long-term average rainfall between 1998 and 2014 (see Figure A1 in the supplemental data for the distribution of lagged 3-year SRAI in Thailand and Vietnam for years 2013 and 2016). We use this lagged SRAI as the IV for irrigation variables (i.e. the share of irrigated land areas and the improved share of irrigated land area) in estimating Equation (6). The reason behind the use of this lagged IV is that weather shocks (i.e. extreme rainfall) in previous years might affect the irrigation in the current year. The results from additional estimations showed in Table A7 of the supplemental data indicate that this IV does not correlate with the farming efficiency. Further, we conduct two tests, namely the under-identifying test and weak identifying test to validate this IV. The results of these tests showed in the post-estimation section of Table 5 confirm the use of this IV in our estimations. We check for the multicollinearity problem in our model by using the VIF values. The results of VIF values presented in the second column of Table A2 in the supplemental data do not show a serious problem of multicollinearity. To have robust standard errors and to prevent the problem of auto-correlation, we cluster our estimations at village level.

4.3 Measurement of poverty

Next, we use two different approaches to measure poverty, namely absolute poverty and multidimensional poverty. The absolute poverty is relied on a fixed poverty line at which households are classified as poor if their income or consumption is at or lower than the poverty line (Smith, 2004). In this case, we use the World Bank's poverty threshold for middle-income countries at a daily income per capita of PPP$ 3.20 (World Bank, 2018) because Thailand and Vietnam belong to this middle-income group and our data fall into this proposed period. In addition to this absolute income poverty, we adopt the measure of multidimensional poverty suggested by the World Bank (World Bank, 2020). We adjust this measure and include four dimensions of households' characteristics, namely (i) monetary dimension; (ii) education dimension; (iii) access to basic infrastructure; and (iv) housing and living conditions (detailed measurement of multidimensional parameters is in Panel A4 of Table A1 in the supplemental data). Each of these four dimensions is weighted equally (information of adopted dimensions, indicators, and weights is in Table A3 of the supplemental data). We set the cut-off level at 0.25 (i.e., one-fourth). In other words, a household is classified as living in multidimensional poverty if this household has the total number of parameters adding up to 0.25 or higher.

Table 3. Descriptive summary of household's income and poverty

	Whole sample (n = 10140)	2010		2013		2016	
		Thailand (n = 1681)	Vietnam (n = 1699)	Thailand (n = 1681)	Vietnam (n = 1699)	Thailand (n = 1681)	Vietnam (n = 1699)
A. Household income							
Daily crop income per capita (2005 PPP$)	1.57	1.62	$1.04^{***, a}$	1.89	$1.15^{***, a}$	1.91	1.83^{a}
	(3.63)	(3.22)	(3.39)	(3.44)	(2.81)	(3.90)	(4.65)
Daily total income per capita (2005 PPP$)	6.83	6.60	$3.98^{***, a}$	7.62	$4.93^{***, a}$	10.47	$7.43^{***, a}$
	(20.34)	(19.39)	(5.42)	(23.31)	(6.33)	(37.56)	(8.29)
B. Parameters of multidimensional poverty							
No schooling of school-age children (yes = 1)	0.06	0.06	0.05^{b}	0.11	$0.08^{***, b}$	0.02	0.03^{b}
	(0.24)	(0.24)	(0.22)	(0.31)	(0.28)	(0.15)	(0.16)
No primary education of adult members (yes = 1)	0.02	0.04	$0.02^{***, b}$	0.03	$0.01^{***, b}$	0.02	$0.01^{***, b}$
	(0.15)	(0.20)	(0.14)	(0.18)	(0.11)	(0.13)	(0.09)
Asset poor (yes = 1)	0.20	0.20	0.20^{b}	0.20	0.20^{b}	0.20	0.20^{b}
	(0.40)	(0.40)	(0.40)	(0.40)	(0.40)	(0.40)	(0.40)
Unsafe drinking water (yes = 1)	0.38	0.16	$0.67^{***, b}$	0.12	$0.69^{***, b}$	0.04	$0.60^{***, b}$
	(0.49)	(0.37)	(0.47)	(0.33)	(0.46)	(0.21)	(0.49)
No improved sanitation (yes = 1)	0.30	0.03	$0.70^{***, b}$	0.02	$0.60^{***, b}$	0.01	$0.45^{***, b}$
	(0.46)	(0.17)	(0.46)	(0.15)	(0.49)	(0.09)	(0.50)
No access to electricity for lighting (yes = 1)	0.02	0.02	$0.01^{**, b}$	0.04	$0.02^{**, b}$	0.01	$0.02^{***, b}$
	(0.14)	(0.15)	(0.11)	(0.19)	(0.15)	(0.10)	(0.15)
Malnourished child (yes = 1)	0.12	0.14	$0.18^{***, b}$	0.11	$0.15^{***, b}$	0.07	$0.10^{***, b}$
	(0.33)	(0.34)	(0.38)	(0.31)	(0.36)	(0.25)	(0.30)
Inadequate housing conditions (yes = 1)	0.16	0.11	$0.30^{***, b}$	0.20	0.19^{b}	0.05	$0.11^{***, b}$
	(0.37)	(0.31)	(0.46)	(0.40)	(0.39)	(0.22)	(0.31)
C. Poverty indicators							
Absolute income poverty at PPP$ 3.20 per capita a day (yes = 1)	0.42	0.42	$0.60^{***, b}$	0.44	$0.52^{***, b}$	0.24	$0.32^{***, b}$
	(0.49)	(0.49)	(0.49)	(0.50)	(0.50)	(0.43)	(0.47)
Multidimensional poverty (yes = 1)	0.46	0.44	$0.66^{***, b}$	0.47	$0.59^{***, b}$	0.25	$0.37^{***, b}$
	(0.50)	(0.50)	(0.47)	(0.50)	(0.49)	(0.43)	(0.48)

Notes: Standard deviations in parentheses; ^{a}: Two-sample t-test; ^{b}: Non-parametric two-sample Wilcoxon rank-sum test; $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

Panel A of Table 3 presents the descriptive summary of household incomes. Thai households have significantly higher daily crop income and daily total income per capita compared to Vietnamese households and both income indicators show an increasing trend in two countries. In 2010, the daily crop and total income per capita of households in Thailand are PPP$ 1.62 and PPP$ 6.60, respectively. These amounts increase to PPP$ 1.91 for crop income and PPP$

10.47 for household income in 2016. The daily crop income per capita of households in Vietnam increases from PPP$ 1.04 in 2010 to PPP$ 1.83 in 2016. It is noticeable that the difference of crop income between Thai and Vietnamese households becomes insignificant in 2016. The daily total income per capita of households in Vietnam increases from PPP$ 3.98 to PPP$ 7.43 between 2010 and 2016, however, these are relatively lower compared with those in Thailand.

The dimensions of multidimensional poverty are presented in Panel B of Table 3. Vietnamese households are more likely to have unsafe drinking water, no improved sanitation, malnourished child, and inadequate housing conditions. The differences in these dimensions are statistically significant over time. On the other hand, Thai households are more likely to have no primary education of adult members. The differences in schooling of school-age children and asset poor are not statistically significant (except for the schooling of school-age children in 2013). Panel C of Table 3 presents the descriptive summary of absolute poverty and multidimensional poverty. Vietnamese households have a higher incidence of poverty.

4.4 Evaluating the impacts of irrigation on household's income and poverty

In the last step, we examine the impacts of irrigation on income and poverty of rural households. As we explained in the previous section that we cannot justify whether the available irrigation is *ex ante* or *ex post* of production season. If the availability of the reported irrigation is after the production season, then the estimation of the impacts of irrigation on household's income and poverty might not be valid. We therefore control for this by using the lagged values of irrigated land shares. The model of fixed-effects estimation with IV for the impacts of irrigation on household's income and poverty can be specified as:

$$\boldsymbol{Y_{it}} = \theta_0 + \theta_1 \boldsymbol{I_{it-3}} + \theta_2 \boldsymbol{S_{it}} + \theta_3 \boldsymbol{H_{it}} + \theta_4 \boldsymbol{V_{jt}} + \mu_{ijt} \qquad (7)$$

In Equation (7), $\boldsymbol{Y_{it}}$ is a group of the income and poverty of household *i* at time *t* which includes (i) crop income per capita, (ii) total income per capita, (iii) income poverty at PPP$ 3.20 per capita per day, and (iv) multidimensional poverty; $\boldsymbol{I_{it-3}}$ is the lagged 3-year share of irrigated land area. $\boldsymbol{S_{it}}$ is the dummy variable of household's exposure to weather shocks. $\boldsymbol{H_{it}}$ and $\boldsymbol{V_{jt}}$ are the household and village characteristics, respectively. μ_{ijt} is the error term. To instrument the lagged share of irrigated land area, we use the same IV of lagged SRAI variable as mentioned in subsection 4.2. The results of additional estimations showed in Table A8 of the supplemental data confirm that this IV does not correlate with the household income variables. Further, the results of under-identifying and weak identifying tests presented in the post-estimation section in Table 6 validate the use of this IV. We check for the sign of multicollinearity by using the VIF values. The results of VIF values presented in the third column of Table A2 in the supplemental data do not show a sign of this problem. We cluster our estimations at village level to have robust standard errors and to prevent the problem of auto-correlation.

5. Results and discussion

5.1 Year-round irrigation at village level and irrigation of rural households

Table 4 shows the factors affecting the share of irrigated land area in the total land area of rural households. As expected, the exposure to weather shocks has a negative and significant association with the share of household's irrigated land area. Particularly, households with weather shock experience have a lower share of irrigated land area by 2.4% in the estimations of year-round irrigation without shock interaction and by 4.0% in the estimation of year-round irrigation with shock interactions. This result is consistent with the findings from Kaini et al. (2021) and Malek et al. (2018) that weather shocks increase water scarcity and reduce the availability of water for irrigation. It appears that having year-round irrigation in the village has a positive and significant correlation with the share of household's irrigated land area. Furthermore, the coefficient of the interaction between weather shocks and year-round irrigation shows that households with shock experience located in villages with year-round irrigation have a higher share of irrigated land area by 2.86%, implying the important role of providing year-round irrigation in the context of weather shocks. In the context of this study, the role of irrigation development is extremely important in our study sites (i.e., Northeast Thailand and Central Vietnam) for smallholders to cope with adverse weather events (Buurman et al., 2020; Suebpongsang et al., 2020). This result is reasonable because the share of irrigated land area has been increasing in the two countries between 2010 and 2016, in spite of increasing weather shocks. The availability of year-round irrigation at village level is significant for rural households to cope with water scarcity and to enhance irrigation for agricultural production at household level (Gatti et al., 2021).

In addition, year-round irrigation with reservoir as the major source of irrigation plays a more significant role in increasing the share of irrigated land area of rural households. Particularly, households located in villages with reservoir year-round irrigation have a higher share of irrigated land area by about 6%. On the other hand, year-round irrigation with main irrigation sources from dams does not have any significant associations with the share of irrigated land area. This result seems valid because many dams in Vietnam have a low value of irrigation per cubic meter and reservoirs play an important role in supplying water for agricultural production (ADB, 2009; ADB, 2020b). Further, multipurpose dams affect irrigation water for agricultural activities due to their regulations on water flows (Foudi et al., 2023). These results are also in line with the descriptive information showed in Table 1 that, in both Thailand and Vietnam, the proportion of villages having year-round irrigation with reservoirs is increasing, while the role of dam in supplying irrigation water is decreasing.

The remaining variables at household level that have a positive and significant correlation with the share of household's irrigated land area include age of heads and number of phones, while the household size, schooling years of heads, mean schooling years of adult members, and household land per capita appear to have a negative and significant association with this irrigated land share. Our results share some similarities with the findings from Schuck et al. (2005) in the case of education that the effect of education on irrigation is different. The negative correlation of education-related variables can be due to the opportunities of higher educated laborers to engage in non-farm employment rather than farm activities implying a decreased focus on farming and irrigation (Do et al., 2022). Regarding village variables, the distance to the provincial capital has a negative and significant correlation with the share of irrigated land area. This is reasonable as the remoter the village is, the lower the availability of irrigation systems is (Lipton et al., 2003).

Table 4. Factors affecting the share of irrigated land area (fixed-effects estimations)

	Year-round irrigation		Year-round irrigation with reservoir		Year-round irrigation with dam	
	Without interaction	With interaction	Without interaction	With interaction	Without interaction	With interaction
Exposure to weather shocks†	-2.399***	-3.950***	-2.267**	-2.463**	-2.178**	-2.074**
	(0.894)	(1.356)	(0.896)	(1.010)	(0.903)	(0.990)
Year-round irrigation in village†	8.047***	7.192***				
	(1.535)	(1.536)				
Year-round irrigation with reservoir†			6.340***	6.068***		
			(1.543)	(1.569)		
Year-round irrigation with dam†					2.823	3.030
					(1.862)	(1.842)
Weather shocks*Year-round irrigation		2.862*				
		(1.729)				
Weather shocks*Year-round with reservoir				1.014		
				(1.999)		
Weather shocks*Year-round with dam						-0.765
						(2.349)
Age of household head	0.222***	0.224***	0.224***	0.224***	0.256***	0.256***
	(0.079)	(0.079)	(0.079)	(0.079)	(0.079)	(0.079)
Male head†	-2.125	-2.042	-2.357	-2.351	-2.669	-2.679
	(2.058)	(2.052)	(2.055)	(2.056)	(2.050)	(2.048)
Ethnic majority†	-8.094	-7.931	-7.683	-7.687	-7.812	-7.840
	(5.590)	(5.580)	(5.490)	(5.494)	(5.603)	(5.609)
Household size	-1.542***	-1.560***	-1.486***	-1.483***	-1.539***	-1.539***
	(0.408)	(0.408)	(0.408)	(0.408)	(0.409)	(0.409)
Share of laborers	-0.033	-0.033	-0.032	-0.032	-0.026	-0.026
	(0.022)	(0.022)	(0.022)	(0.022)	(0.022)	(0.022)
Schooling years of household head	-0.439*	-0.436*	-0.393*	-0.394*	-0.351	-0.353
	(0.230)	(0.229)	(0.230)	(0.230)	(0.230)	(0.230)
Mean schooling years of adult members	-0.607***	-0.616***	-0.632***	-0.633***	-0.673***	-0.671***
	(0.202)	(0.202)	(0.202)	(0.202)	(0.202)	(0.202)
Asset value per capita (ln)	-0.373	-0.369	-0.373	-0.376	-0.282	-0.287
	(0.461)	(0.461)	(0.461)	(0.460)	(0.460)	(0.460)
Number of phones	2.676***	2.680***	2.632***	2.629***	2.649***	2.645***
	(0.363)	(0.363)	(0.364)	(0.365)	(0.366)	(0.366)
Number of tractors	-1.201	-1.200	-0.986	-0.982	-1.108	-1.106
	(0.883)	(0.882)	(0.882)	(0.882)	(0.878)	(0.878)
Number of sprayers	1.059	1.084	1.141	1.152	1.266*	1.267*
	(0.771)	(0.772)	(0.767)	(0.767)	(0.767)	(0.766)
Number of pumps	0.201	0.202	0.233	0.238	0.180	0.181
	(0.674)	(0.675)	(0.678)	(0.679)	(0.674)	(0.674)
Household land per capita (ln)	-4.849***	-4.857***	-4.937***	-4.935***	-5.032***	-5.032***
	(0.617)	(0.616)	(0.616)	(0.616)	(0.611)	(0.611)
Made roads in village†	-0.177	-0.223	0.257	0.256	0.082	0.083
	(1.816)	(1.817)	(1.820)	(1.820)	(1.854)	(1.854)
Share of households with cable internet at home in village	0.104	0.103	0.111*	0.111*	0.100	0.100
	(0.065)	(0.065)	(0.065)	(0.065)	(0.065)	(0.065)
Distance to provincial capital	-0.086*	-0.087*	-0.081	-0.081	-0.086*	-0.085*
	(0.050)	(0.050)	(0.051)	(0.051)	(0.050)	(0.050)
Distance to the closest market	-0.012	-0.008	-0.002	-0.001	-0.016	-0.017
	(0.145)	(0.145)	(0.147)	(0.147)	(0.154)	(0.154)
Constant	58.444***	58.697***	60.092***	60.150***	59.044***	59.092***
	(7.995)	(7.995)	(7.912)	(7.915)	(8.001)	(7.997)
Number of observations	10140	10140	10140	10140	10140	10140
F	12.12	11.66	11.18	10.67	9.98	9.48
Prob > F	0.000	0.000	0.000	0.000	0.000	0.000
R-squared:						
Within	0.043	0.043	0.039	0.039	0.035	0.035
Between	0.244	0.244	0.225	0.225	0.231	0.231
Overall	0.168	0.168	0.153	0.153	0.157	0.157

Notes: Robust standard errors clustered at village level in parentheses; †: Dummy; ln: natural logarithm; *** p<0.01, ** p<0.05, * p<0.1.

5.2 Effects of improved irrigation on household's crop production

The likelihood ratio test between the Cobb-Douglas and translog functional form (Kodde & Palm, 1986) shows that the translog model is more appropriate (see Table A4 in the supplemental data for the result of the test). The results of the translog true random-effects stochastic production frontier function with Mundlak's (reported in Table A5 of the supplemental data) indicate that, in Northeast Thailand and Central Vietnam, farming laborers are the most important input, followed by harvest costs, seedling costs, fertilizer costs, and pesticide costs in crop production. The cost of irrigation also shows a positive correlation with the farming efficiency.

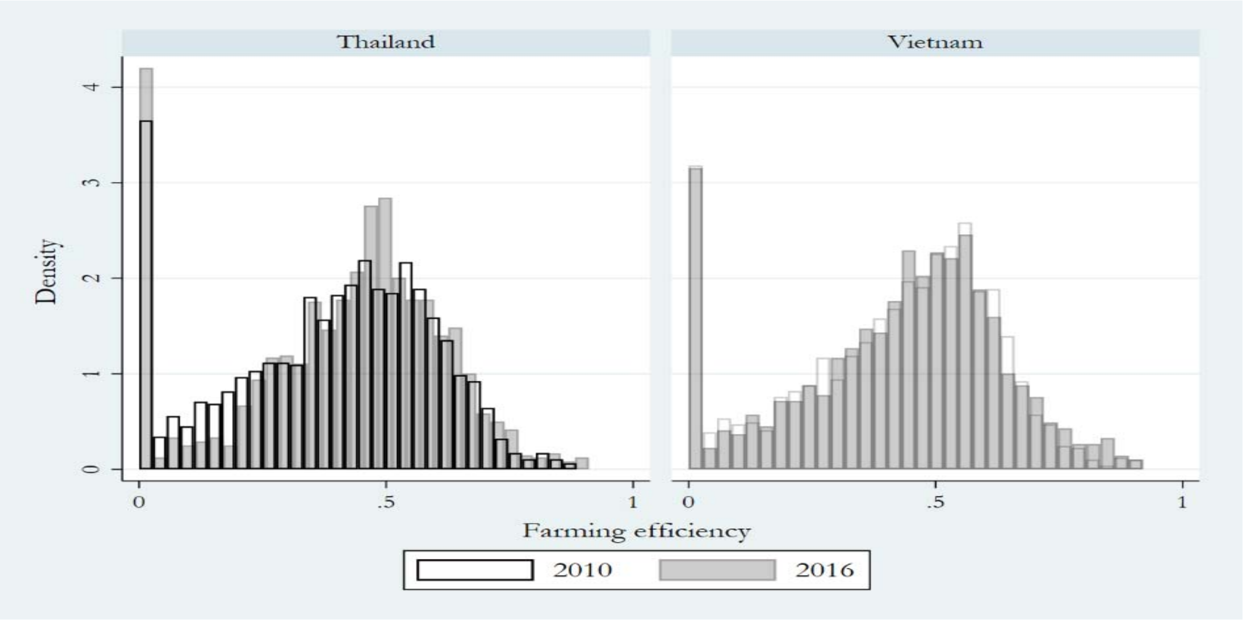


Figure 2. Farming efficiency of crop production in Thailand and Vietnam in 2010 and 2016

Figure 2 shows the distribution of predicted farming efficiency scores in Thailand and Vietnam in 2010 and 2016. About 10% of the observations have the efficiency score of 0.1, about 40% of the observations have the score higher than 0.50, and only 5% have the score higher than 0.70. These figures indicate that there are still large efficiency gaps in farming in both countries. The descriptive summary of crop farming efficiency scores (presented in Table A6 of the supplemental data) shows that the farming efficiency score is about 0.40 on average for the whole sample. At country level, the efficiency score of households in Northeast Thailand is 0.39 in 2010, then it increases to 0.41 in 2013 and remains unchanged in 2016. Meanwhile, the efficiency score of households in Central Vietnam is 0.41 in 2010, decreases to 0.36 in 2013, and stands at 0.42 in 2016.

Table 5. Effects of the share of irrigated land area on farming efficiency (fixed-effects with IV estimations)

	Farming efficiency	
	Share of irrigated land area	Improved share of irrigated land area
Share of irrigated land area	0.001*	
	(0.001)	
Improved share of irrigated land area†		0.053*
		(0.028)
Exposure to weather shocks	-0.014**	-0.030***
	(0.006)	(0.008)
Age of household head	-0.000	0.001
	(0.001)	(0.001)
Male head†	0.020	0.007
	(0.015)	(0.020)
Ethnic majority†	0.086***	0.060
	(0.032)	(0.039)
Household size	0.009***	0.004
	(0.003)	(0.004)
Share of laborers	-0.000*	-0.000
	(0.000)	(0.000)
Schooling years of household head	-0.002	-0.000
	(0.002)	(0.003)
Mean schooling years of adult members	0.001	0.000
	(0.001)	(0.002)
Asset value per capita (ln)	0.011***	0.011**
	(0.003)	(0.005)
Number of phones	-0.004	0.003
	(0.003)	(0.004)
Number of tractors	0.006	-0.005
	(0.007)	(0.009)
Number of sprayers	0.019***	0.028***
	(0.005)	(0.008)
Number of pumps	0.008*	0.021***
	(0.005)	(0.007)
Household land per capita (ln)	0.022***	0.016***
	(0.006)	(0.006)
Made roads in village†	0.001	0.013
	(0.012)	(0.018)
Share of households with cable internet at home in village	-0.000	0.001
	(0.000)	(0.001)
Distance to provincial capital	-0.000	-0.001
	(0.000)	(0.000)
Distance to the closest market	0.000	0.001
	(0.002)	(0.002)
Constant	0.204***	0.181*
	(0.064)	(0.093)
Number of observations	10140	6760
Wald chi2(19)	1561.78	832.42
Prob > chi2	0.000	0.000
Under-identification	0.000	0.000
Weak identification	128.964	238.215

Notes: Robust standard errors clustered at village level in parentheses; †: Dummy variable; ln: natural logarithm; $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$; The under-identification test is an LM test based on the rk LM statistics in which the null hypothesis indicates that the model is under-identified. The reported values of under-identification tests are p-values. The reported test of weak identification is the Kleibergen-Paap rk Wald F statistic which is relied on the proposed significant level from Staiger and Stock (1997).

Table 5 presents the results of the effect of irrigation on farming efficiency of rural households. Regarding the weather shocks, the result is consistent with that of Mishra et al. (2015), Mishra et al. (2018), and Nguyen, Do, and Rahut (2022) that weather shocks negatively affect the efficiency of farming in Bangladesh, Cambodia, and Thailand, respectively. It is evident that reduced precipitation results in yield decrease, particularly in Northeast Thailand and Central Vietnam (Kang et al., 2021). We also find that the share of irrigated land area has a positive and significant influence on farming efficiency. Besides, the improved share of irrigated land area in the current period (compared with the previous period) also shows a positive and significant impact of irrigation development on farming efficiency. In the context of our study, in countries such as Thailand and Vietnam where rural households are facing increasing adverse weather events, better irrigation improves crop farming efficiency by reducing the efficiency losses due to weather shocks. Furthermore, in Northeast Thailand where farming relies more on rainfall, irrigation development is vital for yield increase (Suwanmontri et al., 2021).

Our result also shows that ethnic majority positively affects household's farming efficiency. Ethnic minorities are found to be less efficient in farming than the ethnic majority in these two countries due to various factors. They employ less agricultural machines and equipment (Do et al., 2023; Nguyen, Nguyen, and Grote, 2022), have a higher dependency ratio (Huy & Nguyen, 2019), and are poorer (Baulch et al., 2007; Draper & Selway, 2019). In terms of the remaining significant variables, household size, asset value per capita, number of sprayers and pumps, and household land per capita have a positive effect on farming efficiency. These results are consistent with the findings from Do et al. (2023) for agricultural machines and equipment, Huy and Nguyen (2019) in the case of household size and poor households, and Nguyen et al. (2018) regarding land area.

5.3 Impacts of irrigation on household's income and poverty

Table 6 presents the impact of irrigation on household's income and poverty. The results depicts some important findings. First, the exposure to weather shocks negatively and significantly affects the income from crops which is in the same vein as the findings from Amare et al. (2023), especially for Northeast Thailand and Central Vietnam (Nguyen et al., 2020). This seems to be supportive of the result from the effect of weather shocks on crop farming efficiency in the previous section and consistent with the findings from Huang et al. (2006) and Nguyen, Do, and Rahut (2022).

Table 6. Impacts of irrigated land share on household income and poverty (fixed-effects with IV estimations)

	Daily crop income per capita (ln)	Daily total income per capita (ln)	Absolute poverty at PPP$ 3.20†	Multidimensional poverty†
Lagged share of irrigated land area	0.017*	0.030***	-0.006***	-0.007***
	(0.010)	(0.004)	(0.001)	(0.001)
Exposure to weather shocks	-0.342*	0.041	0.009	-0.013
	(0.207)	(0.086)	(0.019)	(0.020)
Age of household head	0.007	0.007	-0.002	-0.001
	(0.020)	(0.007)	(0.002)	(0.002)
Male head†	0.304	-0.189	-0.021	0.015
	(0.457)	(0.180)	(0.044)	(0.043)
Ethnic majority†	0.994	1.040***	-0.236***	-0.245***
	(0.922)	(0.339)	(0.082)	(0.083)
Household size	0.097	-0.098**	0.025***	0.041***
	(0.098)	(0.039)	(0.009)	(0.009)
Share of laborers	-0.001	0.004*	-0.001**	-0.001*
	(0.005)	(0.002)	(0.001)	(0.001)
Schooling years of household head	-0.039	0.021	0.004	0.001
	(0.064)	(0.021)	(0.006)	(0.006)
Mean schooling years of adult members	0.030	-0.017	-0.000	0.001
	(0.044)	(0.017)	(0.004)	(0.004)
Asset value per capita (ln)	0.173	0.100**	-0.051***	-0.053***
	(0.119)	(0.045)	(0.010)	(0.010)
Number of phones	-0.043	0.022	-0.005	-0.009
	(0.083)	(0.028)	(0.007)	(0.007)
Number of tractors	0.221	-0.058	0.031	0.052***
	(0.222)	(0.083)	(0.020)	(0.020)
Number of sprayers	0.810***	0.050	-0.024*	-0.022
	(0.204)	(0.063)	(0.013)	(0.013)
Number of pumps	0.461***	0.165**	-0.021	-0.024
	(0.145)	(0.068)	(0.015)	(0.015)
Household land per capita (ln)	0.499***	-0.026	-0.000	0.001
	(0.124)	(0.046)	(0.011)	(0.011)
Made roads in village†	0.625	0.393***	-0.121***	-0.098***
	(0.386)	(0.152)	(0.030)	(0.028)
Share of households with cable internet at home in village	0.017	0.012***	-0.002***	-0.002***
	(0.016)	(0.004)	(0.001)	(0.001)
Distance to provincial capital	-0.001	0.002	-0.000	-0.000
	(0.008)	(0.003)	(0.001)	(0.001)
Distance to the closest market	-0.025	-0.011	0.002	0.001
	(0.040)	(0.013)	(0.003)	(0.003)
Constant	-1.423	-2.956***	1.452***	1.460***
	(1.830)	(0.696)	(0.172)	(0.169)
Number of observations	6760	6760	6760	6760
Wald chi2(19)	132.37	187.11	549.42	637.45
Prob > chi2	0.000	0.000	0.000	0.000
Under-identification	0.000	0.000	0.000	0.000
Weak identification	237.436	237.436	237.436	237.436

Notes: Robust standard errors clustered at village level in parentheses; †: Dummy variable; ln: natural logarithm; *** p<0.01, ** p<0.05, * p<0.1; The under-identification test is an LM test based on the rk LM statistics in which the null hypothesis indicates that the model is under-identified. The reported values of under-identification tests are p-values. The reported test of weak identification is the Kleibergen-Paap rk Wald F statistic which is relied on the proposed significant level from Staiger and Stock (1997).

Second, the lagged share of irrigated land area has a positive and significant impact on daily crop income per capita and daily total income per capita. These results appear to be reasonable because, from the context of our study, rural households in Northeast Thailand and Central

Vietnam have better crop income along with better irrigation (Ho et al., 2022; Suebpongsang et al., 2020). Our results of the impacts of irrigation on household income are in the same vein as those from Dillon (2011), Huang et al. (2006), and Hussain (2007). Third, we further find that the lagged share of irrigated land area has a negative and significant influence on rural households' absolute poverty at PPP$ 3.20 and multidimensional poverty. This indicates the role of irrigation in reducing poverty. While the result of absolute poverty is similar to that of Senaratna Sellamuttu et al. (2014) and Smith (2004), the impact of irrigation on multidimensional poverty from our study sheds further light on the important role of irrigation in contributing to poverty eradication in multidimensions.

In addition, among the household variables, households from the ethnic majority have better income and a lower incidence of poverty. This result is consistent with that from Baulch et al. (2007) and Draper and Selway (2019). This implies that a better support to ethnic minorities to help them improve their income, reduce their poverty status, and shorten the income gap with the ethnic majority is needed. The focus of this support can be placed on asset poor households to help them escape poverty (Do et al., 2022). At village level, better infrastructure for transportation and ICT has a positive and significant impact on household income and a negative and significant impact on poverty. Our finding of the internet's impacts is consistent with that from Nguyen, Nguyen, and Grote (2022) and it implies that the development of irrigation should come hand-in-hand with infrastructure development such as better roads or ICT access to have a higher synergy in improving income and reducing poverty in rural areas. Further consideration of development policies on irrigation can also put emphasis on smallholders' collective organization (Llones et al., 2022; Nguyen et al., 2023).

6. Summary and policy implications

Improving irrigation for agricultural production is important for poverty reduction and food security, especially in coping with more frequent weather shocks. In this study, we examine how year-round irrigation at village level can have an association with the development of irrigation at household level and help rural households cope with weather shocks. We also investigate the effects of irrigation on farming efficiency, income, and poverty. We use panel data of 1,681 households in Northeast Thailand and 1,699 households in Central Vietnam collected in 2010, 2013, and 2016 with a total of 10,140 observations. A true random-effects translog stochastic frontier production estimation with Mundlak's adjustments is used to estimate farming efficiency. We address the problems of unobserved heterogeneity and endogeneity by using an instrumental variable approach. Our empirical results produce several important findings.

Regarding the first research question of the association between village's year-round irrigation and household's irrigated land, our results show that the availability of village's year-round irrigation in Northeast Thailand and Central Vietnam has a positive association with the share of household's irrigated land area. Further, while weather shocks have a negative association with household's irrigated land share, the availability of village's year-round irrigation helps increase this household's irrigated land share under the adverse impacts of weather shocks. Our results also show that village's year-round irrigation with reservoirs as the major source of irrigation has a more significant correlation with household's irrigated land share than the village's year-round irrigation with dams as the major irrigation source.

With regard to the second research question about the effects of irrigation on farming efficiency, we find that the share of irrigated land area has a positive effect on crop farming efficiency of households in Northeast Thailand and Central Vietnam. The positive influence of irrigation remains consistent when we use improved share of irrigated land area (compared with the previous period). This indicates that a better irrigation increases crop farming efficiency of rural households. Our answer to the last research question of how irrigation affects household's income and poverty is that the lagged share of irrigated land area has a positive effect on household's crop income and total income. It also has a negative impact on poverty in absolute and multidimensional terms. These results imply that irrigation development contributes significantly to poverty eradication in our study sites.

These findings have important policy implications with regard to irrigation development for fighting against increasing weather shocks and poverty. First, policy makers in developing countries and international donors should pay more attention to irrigation development and water management to increase the availability and sustainability of water for irrigation in order to ensure more efficient farming and increase income of farmers in rural regions. Increasing water scarcity induced by climate-driven changes and the rising demand for water from other economic sectors pose a significant risk to agricultural production, poverty reduction, and food security around the globe. In the context of more frequent weather shocks, having access to irrigation is not sufficient for farmers but year-round irrigation. This calls for more sustainable water management and irrigation development in rural regions of developing countries.

Second, the development of irrigation infrastructure such as water reservoirs should be carefully considered to ensure the effectiveness in ensuring year-round irrigation at village level and improving irrigation at household level. We recommend that irrigation development projects should take into account the conditions of local area, the conceptualization of Water – Energy – Food nexus, and sustainable livelihoods for sustainable development. These projects should further consider combining them with more efficient irrigation technologies at farm levels to ensure the availability of water. These irrigation development projects should also balance water scarcity with sustainability to minimize losses in biodiversity and negative effects on the local environment. Last, the development of infrastructure for irrigation should also come with infrastructure development for transportation and ICT. Along with a better irrigation, improved rural roads and ICT significantly increase rural households' income and reduce poverty. The availability of ICT further stimulates the application of technologies for more efficient irrigation.

Although our paper has provided some useful insights, it still has some limitations. First, the impact of climate change could be long-lasting and our panel data might not well reflect the true intensity of weather shocks induced by climate change. Second, we used a dummy variable to represent weather shocks and did not take into account different types of weather shocks. The use of the dummy variable might not well capture the intensity of shocks and we could not examine the heterogeneous effects of shock types. We thus suggest that future studies on assessing the impact of weather shocks on irrigation development should have more appropriate data for reflecting the intensity of weather shocks and also take into account different types of weather shocks. Furthermore, future studies can also examine the effects of particular irrigation methods on household's farming efficiency and welfare to provide more specific implications for better water management at household level.

References

Abdulai, A., & Tietje, H. (2007). Estimating technical efficiency under unobserved heterogeneity with stochastic frontier models: application to northern German dairy farms. *European Review of Agricultural Economics*, *34*(3), 393-416.

ADB. (2009). Water: Vital for Vietnam's future. The Asian Development Bank (ADB) https://www.adb.org/sites/default/files/publication/29806/water-vital-vietnam-future.pdf (Access date: 16/08/2022)

ADB. (2020a). Asian water development outlook: advancing water security across Asia and the Pacific. The Asian Development Bank (ADB). http://dx.doi.org/10.22617/SGP200412-2

ADB. (2020b). Irrigation Systems for Climate Change Adaptation in Viet Nam. The Asian Development Bank (ADB). https://www.adb.org/publications/irrigation-climate-change-adaptation-viet-nam (Access date: 16/08/2022)

Amare, M., Parvathi, P., & Nguyen, T. T. (2023). Micro insights on the pathways to agricultural transformation: Comparative evidence from Southeast Asia and Sub-Saharan Africa. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *71*(1), 69-87.

Aryal, J.P., Rahut, D.B., & Marenya, P. (2021). Climate Risks, Adaptation and Vulnerability in Sub-Saharan Africa and South Asia. In: Alam, G.M.M., Erdiaw-Kwasie, M.O., Nagy, G.J., Leal Filho, W. (eds) Climate Vulnerability and Resilience in the Global South. Climate Change Management. Springer, Cham. https://doi.org/10.1007/978-3-030-77259-8_1

Ashley, C., & Carney, D. (1999). *Sustainable livelihoods: Lessons from early experience* (Vol. 7, No. 1). London: Department for International Development.

Balasubramanya, S., Brozović, N., Fishman, R., Lele, S., & Wang, J. (2022). Managing irrigation under increasing water scarcity. *Agricultural Economics*.

Baulch, B., Chuyen, T. T. K., Haughton, D., & Haughton, J. (2007). Ethnic minority development in Vietnam. *The Journal of Development Studies*, *43*(7), 1151-1176.

Belotti, F., Daidone, S., Ilardi, G., & Atella, V. (2013). Stochastic frontier analysis using Stata. *The Stata Journal*, *13*(4), 719-758.

Blakeslee, D., Dar, A., Fishman, R., Malik, S., Pellegrina, H. S., & Bagavathinathan, K. S. (2023). Irrigation and the spatial pattern of local economic development in India. *Journal of Development Economics*, *161*, 102997.

Buurman, J., Bui, D. D., & Du, L. T. T. (2020). Drought risk assessment in Vietnamese communities using household survey information. *International Journal of Water Resources Development*, *36*(1), 88-105.

Chamberlin, J., & Ricker-Gilbert, J. (2016). Participation in rural land rental markets in Sub-Saharan Africa: Who benefits and by how much? Evidence from Malawi and Zambia. *American Journal of Agricultural Economics*, *98*(5), 1507-1528.

Dillon, A. (2011). The effect of irrigation on poverty reduction, asset accumulation, and informal insurance: Evidence from Northern Mali. *World Development*, *39*(12), 2165-2175.

Do, M. H., Nguyen, T. T., & Grote, U. (2023). Land consolidation, rice production, and agricultural transformation: Evidence from household panel data for Vietnam. *Economic Analysis and Policy*, *77*, 157-173.

Do, M. H., Nguyen, T. T., Halkos, G., & Grote, U. (2022). Non-farm employment, natural resource extraction, and poverty: evidence from household data for rural Vietnam. *Environment, Development and Sustainability*, 1-38.

Draper, J., & Selway, J. S. (2019). A new dataset on horizontal structural ethnic inequalities in Thailand in order to address Sustainable Development Goal 10. *Social Indicators Research*, *141*(1), 275-297.

Eckstein, D., Künzel, V., Schäfer, L., & Winges, M. (2020). *Global Climate Risk Index 2020: who suffers most from extreme weather events? Weather-related loss events in 2018 and 1999–2018*. Germanwatch, Bonn. https://germanwatch.org/sites/default/files/20-2-01e%20Global%20Climate%20Risk%20Index%202020_14.pdf. (Access date: 16/08/2022)

Foudi, S., McCartney, M., Markandya, A., & Pascual, U. (2023). The impact of multipurpose dams on the values of nature's contributions to people under a water-energy-food nexus framing. *Ecological Economics*, *206*, 107758.

Gatti, N., Baylis, K., & Crost, B. (2021). Can irrigation infrastructure mitigate the effect of rainfall shocks on conflict? Evidence from Indonesia. *American Journal of Agricultural Economics*, *103*(1), 211-231.

Gautam, M., & Ahmed, M. (2019). Too small to be beautiful? The farm size and productivity relationship in Bangladesh. *Food Policy*, *84*, 165-175.

Greene, W. (2005). Reconsidering heterogeneity in panel data estimators of the stochastic frontier model. *Journal of Econometrics*, *126*(2), 269-303.

Hamududu, B. H., & Ngoma, H. (2020). Impacts of climate change on water resources availability in Zambia: implications for irrigation development. *Environment, Development and Sustainability*, *22*(4), 2817-2838.

Hardeweg, B., Klasen, S., & Waibel, H. (2013). Establishing a database for vulnerability assessment. In *Vulnerability to Poverty: Theory, measurement and determinants, with case studies from Thailand and Vietnam* (pp. 50-79). Palgrave Macmillan, London.

Ho, T. Q., Hoang, V. N., & Wilson, C. (2022). Sustainability certification and water efficiency in coffee farming: The role of irrigation technologies. *Resources, Conservation and Recycling*, *180*, 106175.

Holtkamp, J., & Brümmer, B. (2017). Stochastic frontier analysis using SFAMB for Ox. *Journal of Statistical Software*, *81*(6).

Huang, Q., Rozelle, S., Lohmar, B., Huang, J., & Wang, J. (2006). Irrigation, agricultural performance and poverty reduction in China. *Food Policy*, *31*(1), 30-52.

Hussain, I. (2007). Direct and indirect benefits and potential disbenefits of irrigation: evidence and lessons. *Irrigation and Drainage*, *56*(2-3), 179-194.

Hussain, I., & Hanjra, M. A. (2004). Irrigation and poverty alleviation: review of the empirical evidence. *Irrigation and Drainage*, *53*(1), 1-15.

Huy, H. T., & Nguyen, T. T. (2019). Cropland rental market and farm technical efficiency in rural Vietnam. *Land Use Policy*, *81*, 408-423.

Jones, P. D., & Hulme, M. (1996). Calculating regional climatic time series for temperature and precipitation: methods and illustrations. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *16*(4), 361-377.

Kaini, S., Nepal, S., Pradhananga, S., Gardner, T., & Sharma, A. K. (2021). Impacts of climate change on the flow of the transboundary Koshi River, with implications for local irrigation. *International Journal of Water Resources Development*, *37*(6), 929-954.

Kandulu, J. M., & Connor, J. D. (2017). Improving the effectiveness of aid: an evaluation of prospective Mekong irrigation investments. *International Journal of Water Resources Development*, *33*(2), 270-291.

Kang, H., Sridhar, V., Mainuddin, M., & Trung, L. D. (2021). Future rice farming threatened by drought in the Lower Mekong Basin. *Scientific Reports*, *11*(1), 9383.

Kim, I. W., Oh, J., Woo, S., & Kripalani, R. H. (2019). Evaluation of precipitation extremes over the Asian domain: observation and modelling studies. *Climate Dynamics*, *52*(3), 1317-1342.

Kodde, D. A., & Palm, F. C. (1986). Wald criteria for jointly testing equality and inequality restrictions. *Econometrica: Journal of the Econometric Society*, 1243-1248.

Kopolrat, K., Sithithaworn, P., Kiatsopit, N., Namsanor, J., Laoprom, N., Tesana, S., ... & Petney, T. N. (2020). Influence of water irrigation schemes and seasonality on transmission dynamics of Opisthorchis viverrini in the snail intermediate host, Bithynia siamensis goniomphalos in rice paddy fields in Northeast Thailand. *The American Journal of Tropical Medicine and Hygiene*, *103*(1), 276.

Koundouri, P., Nauges, C., & Tzouvelekas, V. (2006). Technology adoption under production uncertainty: theory and application to irrigation technology. *American Journal of Agricultural Economics*, *88*(3), 657-670.

Kummerow, C., Barnes, W., Kozu, T., Shiue, J., & Simpson, J. (1998). The tropical rainfall measuring mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology*, *15*(3), 809-817.

Lenton, R. (1994). Research and development for sustainable irrigation management. *International Journal of Water Resources Development*, *10*(4), 417-424.

Lipton, M., Litchfield, J., & Faurès, J. M. (2003). The effects of irrigation on poverty: a framework for analysis. *Water Policy*, *5*(5-6), 413-427.

Llones, C. A., Mankeb, P., Wongtragoon, U., & Suwanmaneepong, S. (2022). Production efficiency and the role of collective actions among irrigated rice farms in Northern Thailand. *International Journal of Agricultural Sustainability*, 1-11.

Malek, K., Adam, J. C., Stöckle, C. O., & Peters, R. T. (2018). Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses. *Journal of Hydrology*, *561*, 444-460.

Marie, M., Yirga, F., Haile, M., & Tquabo, F. (2020). Farmers' choices and factors affecting adoption of climate change adaptation strategies: evidence from northwestern Ethiopia. *Heliyon*, *6*(4), e03867.

McNamara, I., Nauditt, A., Zambrano-Bigiarini, M., Ribbe, L., & Hann, H. (2021). Modelling water resources for planning irrigation development in drought-prone southern Chile. *International Journal of Water Resources Development*, *37*(5), 793-818.

Mdemu, M. V., Mziray, N., Bjornlund, H., & Kashaigili, J. J. (2017). Barriers to and opportunities for improving productivity and profitability of the Kiwere and Magozi irrigation schemes in Tanzania. *International Journal of Water Resources Development*, *33*(5), 725-739.

Mishra, A. K., Mottaleb, K. A., Khanal, A. R., & Mohanty, S. (2015). Abiotic stress and its impact on production efficiency: The case of rice farming in Bangladesh. *Agriculture, Ecosystems and Environment*, *199*, 146-153.

Mishra, A.K., Bairagi, S., Velasco, M.L., & Mohanty, S., (2018). Impact of access to capital and abiotic stress on production efficiency: Evidence from rice farming in Cambodia. *Land Use Policy*, 79, 215-222.

Muller, M., Biswas, A., Martin-Hurtado, R., & Tortajada, C. (2015). Built infrastructure is essential. *Science*, *349*(6248), 585-586.

Mundlak, Y. (1978). On the pooling of time series and cross section data. *Econometrica: Journal of the Econometric Society*, 69-85.

Nguyen, G., and Nguyen, T. T. (2020). Exposure to weather shocks: A comparison between self-reported record and extreme weather data. *Economic Analysis and Policy*, *65*, 117-138.

Nguyen, T. T., Do, M. H., & Rahut D. (2022). Shock, risk attitude and rice farming: Evidence from panel data for Thailand. *Environmental Challenges*, *6*, 100430.

Nguyen, T. T., Do, M. H., Rahut, D. B., Nguyen, V. H., & Chhay, P. (2023). Female leadership, internet use, and performance of agricultural cooperatives in Vietnam. *Annals of Public and Cooperative Economics*. https://doi.org/10.1111/apce.12434

Nguyen, T. T., Do, T. L., Parvathi, P., Wossink, A., & Grote, U. (2018). Farm production efficiency and natural forest extraction: Evidence from Cambodia. *Land Use Policy*, *71*, 480-493.

Nguyen, T. T., Nguyen, L. D., Lippe, R. S., & Grote, U. (2017). Determinants of farmers' land use decision-making: Comparative evidence from Thailand and Vietnam. *World Development*, *89*, 199-213.

Nguyen, T. T., Nguyen, T. T., & Grote, U. (2022). Internet use, natural resource extraction and poverty reduction in rural Thailand. *Ecological Economics*, *196*, 107417.

Nguyen, T. T., Nguyen, T. T., Do, M. H., Nguyen, D. L., & Grote, U. (2022). Shocks, agricultural productivity, and natural resource extraction in rural Southeast Asia. *World Development*, *159*, 106043.

Nguyen, T. T., Nguyen, T. T., Le, V. H., Managi, S., & Grote, U. (2020). Reported weather shocks and rural household welfare: Evidence from panel data in Northeast Thailand and Central Vietnam. *Weather and Climate Extremes*, *30*, 100286.

Nguyen, T. T., Tran, V. T., Nguyen, T. T., and Grote, U. (2021). Farming efficiency, cropland rental market and income effect: evidence from panel data for rural Central Vietnam. *European Review of Agricultural Economics*, *48*(1), 207-248.

Parry, K., van Rooyen, A. F., Bjornlund, H., Kissoly, L., Moyo, M., & de Sousa, W. (2020). The importance of learning processes in transitioning small-scale irrigation schemes. *International Journal of Water Resources Development*, *36*(sup1), S199-S223.

Poggi, C. (2019). Credit availability and internal migration: evidence from Thailand. *The Journal of Development Studies*, *55*(5), 861-875.

Schuck, E. C., Frasier, W. M., Webb, R. S., Ellingson, L. J., & Umberger, W. J. (2005). Adoption of more technically efficient irrigation systems as a drought response. *International Journal of Water Resources Development, 21*(4), 651-662.

Senaratna Sellamuttu, S., Aida, T., Kasahara, R., Sawada, Y., & Wijerathna, D. (2014). How access to irrigation influences poverty and livelihoods: a case study from Sri Lanka. *Journal of Development Studies*, *50*(5), 748-768.

Smith, L. E. (2004). Assessment of the contribution of irrigation to poverty reduction and sustainable livelihoods. *International Journal of Water Resources Development*, *20*(2), 243-257.

Suebpongsang, P., Ekasingh, B., & Cramb, R. (2020). Commercialisation of rice farming in northeast Thailand. *White gold: the commercialisation of rice farming in the lower Mekong basin*, 39-68. Palgrave Macmillan, Singapore.

Suwanmontri, P., Kamoshita, A., & Fukai, S. (2021). Recent changes in rice production in rainfed lowland and irrigated ecosystems in Thailand. *Plant Production Science*, *24*(1), 15-28.

Tesfaye, A., Bogale, A., Namara, R. E., & Bacha, D. (2008). The impact of small-scale irrigation on household food security: The case of Filtino and Godino irrigation schemes in Ethiopia. *Irrigation and Drainage Systems*, *22*(2), 145-158.

Tortajada, C. (2014). Water infrastructure as an essential element for human development. *International Journal of Water Resources Development*, *30*(1), 8-19.

Tortajada, C., & Biswas, A. K. (2022). Water security, climate change and COP26. *International Journal of Water Resources Development*, *38*(2), 193-198.

Tortajada, C., & González-Gómez, F. (2022). Agricultural trade: Impacts on food security, groundwater and energy use. *Current Opinion in Environmental Science and Health*, *27*.

UN. (2005). Designing household survey samples: Practical guidelines. The department of Economic and Social Affairs of the United Nations (UN). New York: UN. https://unstats.un.org/unsd/demographic/sources/surveys/Handbook23June05.pdf. (Access date: 16/08/2022).

World Bank. (2018). Why the World Bank is adding new ways to measure poverty. The World Bank group (WB). https://blogs.worldbank.org/developmenttalk/why-world-bank-adding-new-ways-measure-poverty. (Access date: 16/08/2022).

World Bank. (2020). Poverty and Shared Prosperity 2020: Reversals of Fortune. The World Bank group (WB). https://openknowledge.worldbank.org/bitstream/handle/10986/34496/9781464816024.pdf (Access date: 16/08/2022).

World Bank. (2022). Poverty headcount ratio at national poverty lines (% of population). The World Bank group (WB). https://data.worldbank.org/indicator/SI.POV.NAHC?end=2020&locations=TH-VN&start=1988 (Access date: 16/01/2023).

Appendices

Table A1. Definition and measurement of variables at household and village levels

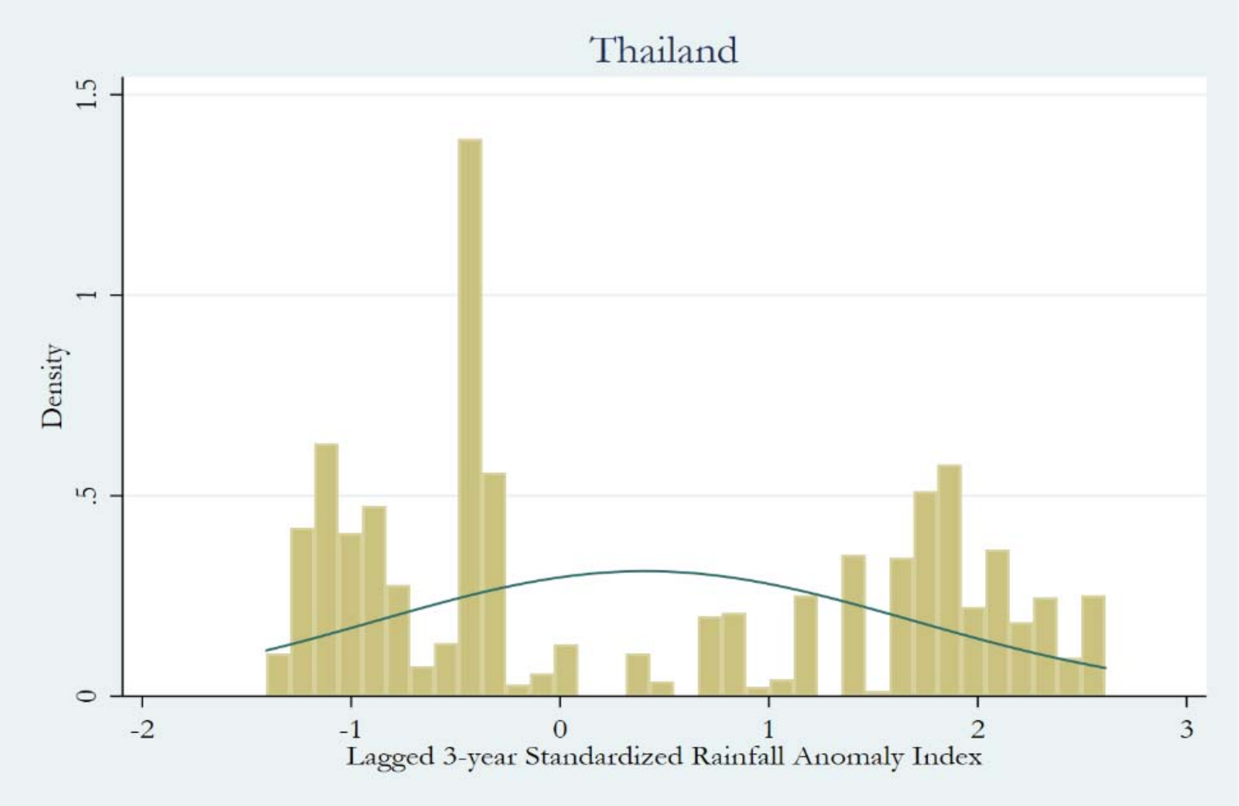
Variables	Measurement	Definition
A. Household level		
A1. Demographic characteristics		
Exposure to weather shocks	Dummy	If the household reports an experience of flooding of agricultural land, drought, landslide and erosion, and storms in the last 12 months of the reference period = 1; otherwise = 0
Age of household head	Years of age	Ages of the household head
Gender of household head	Dummy	Male household head = 1; otherwise = 0
Thai majority (Thailand) or Kinh majority (Vietnam)	Dummy	If the household belongs to Thai majority in Thailand or Kinh majority in Vietnam = 1; otherwise = 0
Household size	Number of persons	Number of members in the household
Share of laborers	Percentage (%)	The share of household members in working age in household size
Schooling years of household head	Years of schooling	Number of schooling years of the household head
Mean schooling years of adult members	Years of schooling	Average schooling years of adult members in the household
A2. Asset and production characteristics		
Household asset value per capita	2005 PPP$ (adjusted to 2005 prices)	Total asset value per capita of the household including productive and non-productive assets
Number of phones	Quantity	Number of phones (mobile and smartphones) that the household owns
Number of tractors	Quantity	Number of 2-wheel and 4-wheel tractors that the household owns
Number of sprayers	Quantity	Number of knapsack and engine sprayers that the household owns
Number of pumps	Quantity	Number of pumps that the household owns
Household land per capita	hectare	Total land of the household per capita
A3. Irrigation and crop production		
Share of irrigated land area in total land area	Percentage (%)	The share of irrigated land area in total land area of the household
Output values	2005 PPP$ (adjusted to 2005 prices)	The values of output from crop production per hectare
Farming area	hectare	The area of household land area used for crop production
Land preparation cost	2005 PPP$ (adjusted to 2005 prices) per ha	Expenditure on land preparations per hectare
Seedling cost	2005 PPP$ (adjusted to 2005 prices) per ha	Expenditure on seedlings per hectare
Weeding cost	2005 PPP$	Expenditure on weeding per hectare

	(adjusted to 2005 prices)	
Fertilizer cost	2005 PPP$ (adjusted to 2005 prices)	Expenditure on fertilizers per hectare
Pesticide cost	2005 PPP$ (adjusted to 2005 prices)	Expenditure on pesticides per hectare
Harvest cost	2005 PPP$ (adjusted to 2005 prices)	Expenditure on harvest including fuels/electricity per hectare
Irrigation cost	2005 PPP$ (adjusted to 2005 prices)	Expenditure on irrigation including fuels/electricity per hectare
Other costs	2005 PPP$ (adjusted to 2005 prices)	Expenditure on other costs (not listed above) per hectare
Farming laborers	Number of persons	Number of laborers engaging in farming activities of the household
A4. Income and multi-dimensional poverty indicators		
Daily crop income per capita	2005 PPP$ (adjusted to 2005 prices)	Daily crop income per capita of the household in the last 12 months
Daily total income per capita	2005 PPP$ (adjusted to 2005 prices)	Daily total income per capita of the household in the last 12 months
No schooling of school-age children	Dummy	The household has at least one school-age child up to the grade-8 age not enrolling in school = 1; otherwise = 0
No primary education of adult members	Dummy	The household has no adults at the grade-9 age or above completed a primary education = 1; otherwise = 0
Asset poor	Dummy	The household is in the group of the 20% poorest asset per capita = 1; otherwise = 0
Unsafe drinking water	Dummy	Drinking water of the household comes from unsafe sources (river, lake, pond…) = 1; otherwise = 0
No improved sanitation	Dummy	There is no flush toilet in the household = 1; otherwise = 0
No access to electricity for lighting	Dummy	There is no access to electricity for lighting in the household = 1; otherwise = 0
Malnourished child	Dummy	There is a malnourished child in the household = 1; otherwise = 0
Inadequate living conditions	Dummy	The average dwelling size of the household is less than 10 m2 per capita = 1; otherwise = 0
B. Village level		
Year-round irrigation	Dummy	If the village has year-round irrigation = 1; otherwise = 0
Year-round irrigation with reservoir	Dummy	If the village has year-round irrigation with reservoir as the major irrigation source = 1; otherwise = 0
Year-round irrigation with dam	Dummy	If the village has year-round irrigation with dam as the major irrigation source = 1; otherwise = 0
Having made roads instead of dirt roads	Dummy	If the main roads in the village are made roads instead of dirt roads = 1; otherwise = 0
Share of households with cable internet at home	Percentage (%)	The percentage of households with cable internet at home in village
Distance to provincial capital	Kilometer (km)	The distance from the village to the province center
Distance to the closest market	Kilometer (km)	The distance from the village to the closest market

Table A2. Variance Inflation Factor (VIF) values

	(1) Factors affecting irrigation	(2) Effects of irrigation on farming efficiency	(3) Effects of irrigation on income and poverty
Year-round irrigation in village†	1.05		
Share of irrigated land area		1.42	
Lagged share of irrigated land area			1.29
Exposure to weather shocks†	1.05	1.05	1.05
Age of household head	1.20	1.20	1.22
Male head†	1.10	1.10	1.10
Ethnic majority†	1.25	1.24	1.24
Household size	1.47	1.50	1.52
Share of laborers	1.22	1.22	1.23
Schooling years of household head	1.58	1.58	1.54
Mean schooling years of adult members	1.39	1.40	1.38
Asset value per capita (ln)	1.63	1.64	1.57
Number of phones	1.21	1.22	1.19
Number of tractors	1.29	1.29	1.30
Number of sprayers	1.19	1.21	1.21
Number of pumps	1.24	1.26	1.26
Household land per capita (ln)	1.53	1.70	1.60
Made roads in village†	1.14	1.16	1.15
Share of households with cable internet at home in village	1.11	1.11	1.12
Distance to provincial capital	1.18	1.19	1.19
Distance to the closest market	1.20	1.21	1.23
Mean VIF	**1.27**	**1.30**	**1.28**

Notes: †: Dummy variable; ln: natural logarithm



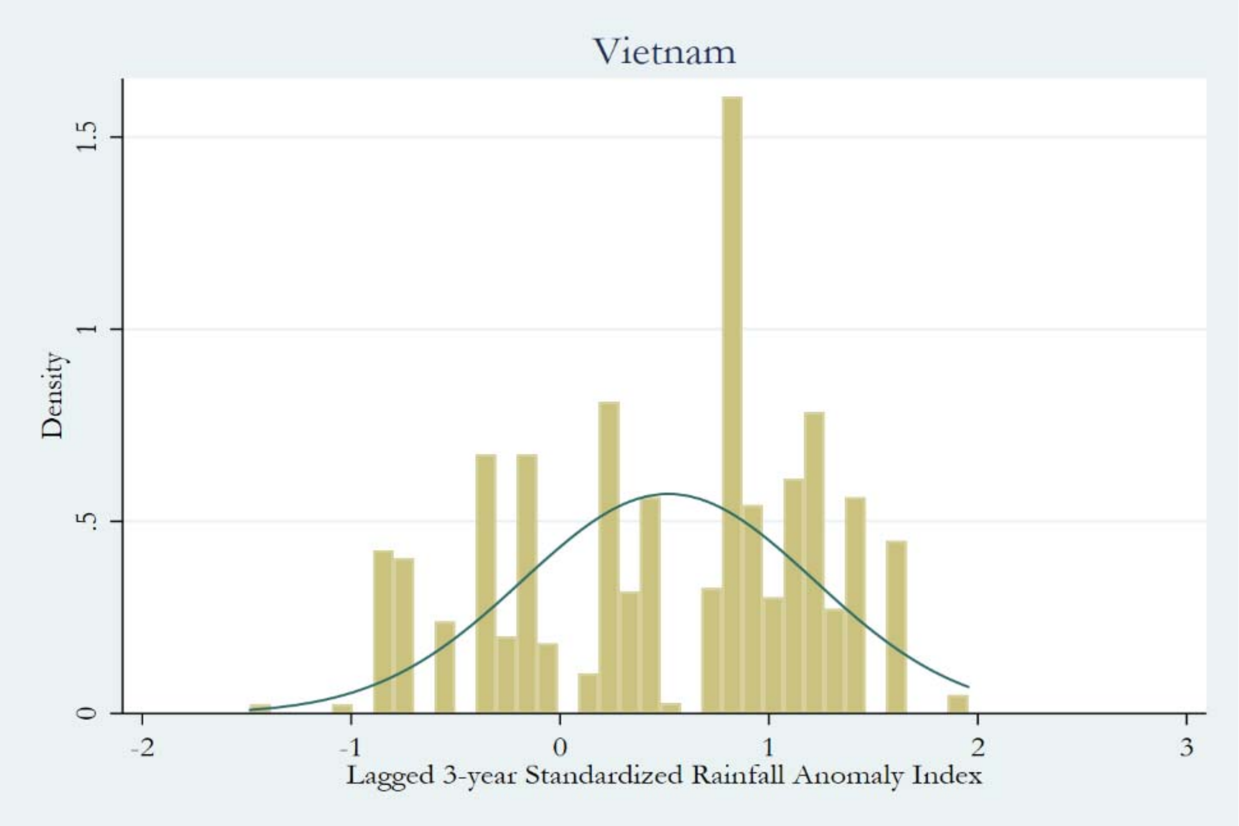


Figure A1. Distribution of the lagged Standardized Rainfall Anomaly Index in Thailand and Vietnam for the year of 2013 and 2016

Table A3. Measurement of multidimensional poverty

Dimension	Parameter	Weight
Monetary dimension	Daily income per capita of the household is at/lower than PPP$ 3.20	1/4
Educational dimension	The household has at least one school-age child up to the grade-8 age not enrolling in school	1/8
	The household has no adults at the grade-9 age or above completed a primary education	1/8
Access to basic infrastructure	The household belongs to the group of 20% poorest in asset value per capita	1/16
	Drinking water of the household comes from unsafe sources	1/16
	There is no improved sanitation (flush toilet) in the household	1/16
	There is no access to electricity for lighting in the household	1/16
Housing and living conditions	There is a malnourished child in the household	1/8
	The average dwelling size of the household is less than 10 m2 per capita	1/8

Table A4. Likelihood ratio test between the Cobb-Douglas and translog functional forms

	Likelihood ratio test $\lambda = -2 * (log\widehat{\Omega}_{H0} - log\widehat{\Omega}_{H1})$	p-value [a]
H0: The production function from Cobb-Douglas is more appropriate	2507.332	0.000

Notes: $log\widehat{\Omega}_{H0}$is the log likelihood of retricted model under the null hypothesis; $log\widehat{\Omega}_{H1}$is the log likelihood of the alternative hypothesis;

[a] compared with the critical value from Kodde and Palm (1986).

Table A5. Results of the translog stochastic frontier production estimation from the true random-effects with Mundlak's adjustments

	Coefficient	Robust S.E.[a]
Farming area (ln) (a)	-0.266***	0.085
Land preparation costs (ln) (b)	-0.001	0.025
Seedling costs (ln) (c)	0.126***	0.020
Weeding costs (ln) (d)	0.011	0.023
Fertilizer costs (ln) (e)	0.092**	0.042
Pesticide costs (ln) (f)	0.041**	0.019
Harvest costs (ln) (g)	0.133***	0.024
Irrigation costs (ln) (h)	0.041*	0.024
Other costs (ln) (i)	0.033*	0.019
Farming laborers (ln) (j)	0.373***	0.108
a^2	0.041	0.036
b^2	0.001	0.004
c^2	0.026***	0.003
d^2	0.004	0.005
e^2	0.041***	0.005
f^2	0.008**	0.004
g^2	0.020***	0.003
h^2	0.017***	0.004
i^2	0.013***	0.004
j^2	0.022	0.064
a*b	0.045***	0.015
a*c	-0.028***	0.008
a*d	-0.006	0.012
a*e	-0.040	0.024
a*f	-0.009	0.011
a*g	0.080***	0.013
a*h	0.010	0.013
a*i	0.018	0.012
a*j	0.196***	0.075
b*c	-0.003	0.003
b*d	0.010**	0.004
b*e	-0.004	0.006
b*f	0.010**	0.004
b*g	-0.008***	0.003
b*h	-0.004	0.003
b*i	0.003	0.004
b*j	0.038*	0.020
c*d	-0.004	0.004
c*e	-0.027***	0.006
c*f	-0.004	0.003
c*g	-0.001	0.003
c*h	0.005*	0.003
c*i	-0.003	0.003
c*j	-0.033*	0.019

d*e	-0.007	0.009
d*f	0.004	0.004
d*g	0.003	0.004
d*h	-0.002	0.004
d*i	0.001	0.004
d*j	0.048*	0.022
e*f	0.000	0.006
e*g	-0.020***	0.006
e*h	-0.026***	0.006
e*i	-0.007	0.006
e*j	-0.092**	0.039
f*g	0.010***	0.003
f*h	0.008**	0.003
f*i	0.001	0.003
f*j	0.060***	0.019
g*h	-0.001	0.003
g*i	0.005	0.004
g*j	-0.039**	0.018
h*i	-0.001	0.003
h*j	0.019	0.019
i*j	0.027	0.020
Mean variables of CRE		
Farming area (ln) (time average-CRE)	0.051	0.056
Land preparation costs (ln) (time average-CRE)	-0.076***	0.017
Seedling costs (ln) (time average-CRE)	-0.012	0.011
Weeding costs (ln) (time average-CRE)	0.017	0.015
Fertilizer costs (ln) (time average-CRE)	0.019	0.025
Pesticide costs (ln) (time average-CRE)	0.052***	0.017
Harvest costs (ln) (time average-CRE)	-0.022	0.014
Irrigation costs (ln) (time average-CRE)	0.073***	0.016
Other costs (ln) (time average-CRE)	0.061***	0.015
Farming laborers (ln) (time average-CRE)	-0.232***	0.079
Constant	8.330***	0.148
Number of observations	10140	
Log simulated-likelihood	-17872.068	
Sigma_u; Sigma_v; Lambda	1.571***; 0.476***; 3.298***	
Wald Chi2(75)	3806.89	
Prob > chi2	0.000	

Notes: [a]: Robust standard errors clustered at village level; ln: natural logarithm; $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

Table A6. Descriptive summary of farming efficiency

	Whole sample (n = 10140)	2010		2013		2016	
		Thailand (n = 1681)	Vietnam (n = 1699)	Thailand (n = 1681)	Vietnam (n = 1699)	Thailand (n = 1681)	Vietnam (n = 1699)
Farming efficiency	0.40	0.39	0.41$^{***, a}$	0.41	0.36$^{***, a}$	0.41	0.42$^{**, a}$
	(0.22)	(0.21)	(0.21)	(0.22)	(0.22)	(0.21)	(0.21)

Notes: Standard deviations in parentheses; ^{a}: Two-sample t-test; *** $p<0.01$, ** $p<0.05$.

Table A7. Validation estimations of the instrumental variable in the estimations of farming efficiency

	Farming efficiency	Share of irrigated land area	Improved share of irrigated land area
Lagged 3-year SRAI	-0.002 (0.003)	-0.111*** (0.007)	-1.841*** (0.550)
Household variables	Yes	Yes	Yes
Village variables	Yes	Yes	Yes
Constant	0.379*** (0.023)	81.361*** (4.322)	0.458*** (0.065)
Number of observations	10,140	10,140	6760
F(19, 439)	22.96	108.34	22.57
Prob. > F	0.000	0.000	0.000

Notes: Robust standard errors clustered at village level in parentheses; *** p<0.01.

Table A8. Validation estimations of the instrumental variable in the estimations of household income

	Daily crop income per capita (ln)	Daily total income per capita (ln)	Lagged share of irrigated land area
Lagged 3-year SRAI	0.005	0.719	8.759^{***}
	(0.051)	(0.358)	(0.621)
Household variables	Yes	Yes	Yes
Village variables	Yes	Yes	Yes
Constant	0.934	-11.443^{***}	81.346^{***}
	(0.471)	(2.114)	(5.431)
Number of observations	6760	6760	6760
F(19, 439)	20.56	19.52	72.12
Prob. > F	0.000	0.000	0.000

Notes: Robust standard errors clustered at village level in parentheses; *** $p<0.01$.