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Multidimensional Impacts of Solar Home Systems: Evidence from Rural Bangladesh

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Abstract

In recent years, the Sustainable Development Goals has managed to shepherd the reduction of energy poverty and extension of sustainable energy, making both international objectives. Using two-period data collected in Bangladesh, we assess the impact of the solar home system (SHS), a promising technology to facilitate multidimensional outcomes from both monetary and non-monetary aspects such as education, health, and security. The results revealed that SHS contributes to the reduced consumption of cow dung and kerosene; extended study hours for children aged 6–15 years; and increased non-farm income and expenditures on food, clothing, and education. However, no significant effect was observed on security and health conditions.

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1. Introduction

The solar home system (SHS), a stand-alone photovoltaic system comprising a solar panel, battery, charge controller, and related devices such as LED lights, has recently attracted worldwide attention given its ability to realize sustainable and renewable energy generation in developing countries without large-scale infrastructure investments (Ellabban *et al.* 2014; Sahu 2015; Solangi *et al.* 2011; Sustainable Energy for All 2014). The SHS is expected to play an important role in achieving Sustainable Development Goal 7, "Ensure access to affordable, reliable, sustainable, and modern energy for all," by 2030 (United Nations 2016).

The SHS is considered to have various functional advantages: (1) reduced consumption of traditional energy sources such as firewood and kerosene (2) increased income by extending income-generating activities at home during night time (3) enhanced educational attainment of children through extended study time (4) improved health conditions of household members by controlling indoor air pollution, and (5) heightened security against fire, theft, and other criminal activities owing to the availability of bright light at night (Khandker *et al.* 2014; Tsuboi 2015).

If these advantages prove to be effective, the SHS will be regarded as an efficient solution to alleviating the multidimensional poverty index (MPI), which has been theoretically established by Alkire and Foster (2011) and widely promoted by Human Development Reports since 2010. This is because the SHS would not only fulfill the need for electricity, a component of MPI itself, but also contribute to other dimensions such as education and health. An empirical research question here is whether, and the extent to which, the SHS has such multidimensional impacts.

However, rigorous impact studies on the SHS and related equipment remain limited and the few exceptions offer controversial results. For example, Khandker *et al.* (2014) showed that the SHS positively impacts income, consumption, and children's study time in Bangladesh—a developing country where the SHS has been rapidly promoted. Kudo *et al.* (2017, forthcoming) conducted an experimental study that comprised a randomized control trial of solar lanterns in the river islands of northern Bangladesh and found that the lanterns increased children's study time and decreased fuel consumption but did not significantly improve the health conditions of household members.

To accumulate more evidence on the impact of the SHS, we conducted a survey during 2014 in the southern coastal area of Bangladesh, Barisal division, where the grid is unavailable and the SHS has been recently introduced. In the survey, we asked SHS users and non-users about the status of certain socioeconomic indicators. As an analysis method, we adopted a household fixed effects model to mitigate the problem of endogeneity in using two-period data.

The results show that the SHS contributes to reduced consumption of cow dung and kerosene; extended study hours for children aged 6–15 years; and increased non-farm income and expenditures on food, clothing, and education. However, we found no significant effect on security (e.g., fire and theft) and health conditions (i.e., cough, headache, sore eyes, and skin burns).

The remainder of this paper is organized as follows. Section 2 briefly summarizes the diffusion of the SHS in Bangladesh. Section 3 explains the analytical framework, survey, and statistical method. Section 4 presents the estimation results and Section 5 concludes the paper.

2. Diffusion of SHS in Bangladesh

Energy poverty, which is the lack of access to modern energy sources, is a primary issue in Bangladesh. Although its national electrification ratio has improved from 22% in 1990 to 60% in 2012, there is a large disparity between urban (90%) and rural (40%) areas (International Energy Agency and the World Bank 2015; World Bank 2015). Bangladesh's government aims to achieve full coverage of electricity by 2021 and the SHS is considered an efficient means of energy generation, especially in rural and geographically disadvantaged areas, where the extension of the grid tends to be delayed.

To promote the SHS in Bangladesh, the government is working toward implementing programs in cooperation with foreign aid agencies. For example, the Rural Electrification and Renewable Energy Development Project (RERED) began in 2003 and installed more than 3 million systems by 2014, funded by the World Bank and other agencies (Khandker *et al.* 2014). Thus far, the SHS has been diffused particularly in the northeast (Sylhet division) and southern (Barisal division) regions. The second phase of the project aims at 6 million installations by 2017 (Infrastructure Development Company Limited 2014).

The project is implemented by the Infrastructure Development Company Limited (IDCOL) and its partner organizations (POs) that directly sell the SHS to households. Among the 47 POs, Grameen Shakti (GS) has the largest market share in SHS installations with a nationwide network of the Grameen family of organizations, including Grameen Bank. **Table 1** show the standard composition of the SHS and the price list of packages sold by GS. Customers can choose a package from a variety of system capacities and pay for the purchase over a maximum of three years in installments.

This payment system has contributed to its rapid diffusion, even in relatively poor rural areas. In general, it is known that rural electrification programs are confronted with the institutional, technological, economic, and contextual barriers in the phase of scaling up (Bonan *et al.* 2017). In the context of SHS programs, the economic barrier is one of the most difficult challenges, as reported in many countries (e.g., Chauhan and Saini [2015] for India, Lee *et al.* [2016] for Kenya, and Ahlborg and Hammar [2014] for Tanzania and Mozambique). The payment system in which consumers make an initial down payment based on affordability and pay the balance of capital costs in installments over a specified period has successfully overcome the barrier in Bangladesh (Asif and Barua 2011; Khandker *et al.* 2014).

Table 1. Example price list for solar home system (Grameen Shakti)

System capacity (watt)	Equipment to be supplied by Grameen Shakti	Package Price (BDT)			
		In cash	Installment		
			1 year	2 years	3 years
20	20 watt panel, 3 x 3 watt LED light, 20/23 AH battery, charge controller, frame, and cables	10,000	11,000	11,500	12,000
40/42	40/42 watt panel, 3 x 3 watt LED tube light, 40/45 AH battery, charge controller, frame, and cables	17,000	19,000	20,000	22,000
60	60 watt panel, 5 x 3 watt LED tube light, a 60 AH battery, charge controller, frame, and cables	23,000	26,000	28,000	30,600
80	80 watt panel, 7 x 3 watt LED tube light, a 80 AH battery, charge controller, frame, and cables	28,000	30,000	32,000	36,600

Source: Grameen Shakti (http://www.gshakti.org/)
Note: 1 USD = 76.9 Taka (as of December 31, 2016).

3. Methodology

3.1 Analytical framework

In terms of welfare, the diffusion of the SHS is expected to contribute to not only income generation but also improvements in the non-monetary aspects of life such as health and education. Recently, the latter aspects have been intensively analyzed in the concept of MPI. The benefits of the SHS can also be considered in the MPI framework, which comprises the three dimensions of living standard, health, and education (**Figure 1**).

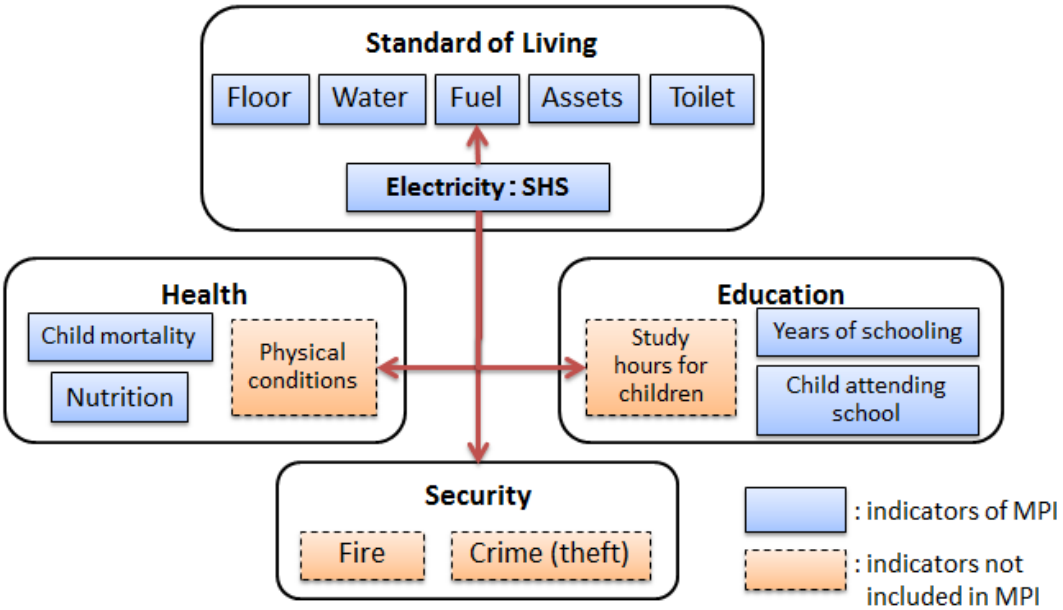

Figure 1. Impacts of solar home system in the multidimensional poverty index

First, "access to electricity" itself is included as a component of the living standard dimension. This may reduce the consumption of "dirty" fuel (e.g., firewood and cow dung), which is another component in the same dimension. Second, the SHS can increase children's study hours during the evening, thus contributing to the education. Third, in the health dimension, positive effects on physical conditions are expected because the LED light in the SHS substitutes kerosene lamps and biomass that puts people at the risk of skin burns, sore eyes, and respiratory diseases owing to indoor air pollution. Fourth, the SHS may deter crimes (e.g., theft of livestock and other assets) and house fires. Although the dimension of security has not been formally included in the MPI, it is an important aspect of welfare.

In addition to non-monetary welfare, the SHS can contribute to income generation activities with longer working hours by providing lighting in houses at night and saving time otherwise spent in the collection of firewood and cow dung. Therefore, both income and expenditure are expected to increase. Although it is unclear which income sources and expenditure items are ex ante sensitive to the adoption of the SHS, such improvements in the monetary aspects will have a positive impact on non-monetary welfare such as living standards, education, and health. In other words, the SHS is expected to have "direct effects" on the MPI as well as "indirect effects" through income and expenditure. Therefore, we focus on the non-monetary as well as monetary impacts of SHS.

3.2 Survey

To evaluate the impacts of the SHS, a household survey was conducted from March to April 2014. We carefully selected survey areas because it is impossible to find households who purchased the SHS (hereafter, "SHS users") in villages where the SHS has not been diffused yet, and because it might be difficult to sample households who did not purchase SHS ("non-users") in villages where the SHS has already been diffused sufficiently. In consultation with GS, we selected five districts—Barisal, Barguna, Jhalakati, Patuakhali, and Pirojpur—in the Barisal division, where SHS had been sold the most among all divisions during the preparation phase of our survey. Under the environment in the process of diffusion, we can sample both SHS users and non-users within the same village.

In cooperation with GS, SHS users were randomly sampled from the customer list in the survey areas. In addition, non-users were identified near SHS users within the same off-grid villages and surveyed for comparative purposes. Such a sampling method enables us to collect information on both users and non-users located in similar natural environments, including climate and other geographical features, which are basic and crucial factors for the feasibility of SHS. The final sample consisted of 232 SHS users and 245 non-users.

Owing to budget and time constraints, we constructed a two-period dataset by simultaneously asking SHS users and non-users about their socioeconomic status for 2012 and 2013. This evaluation method is called a "shoestring evaluation," where a respondent answers questions about the current and past status in the same survey with retrospective recall (Bamberger 2011). Although such methods can be subject to a large bias in memories from, for example, 10 years ago (Ravallion 2014), such a bias may be limited given that respondents had to recall information from the immediately preceding two years in our survey. By constructing the two-period dataset, we estimate the impacts of the SHS using panel data methods.

The questionnaire comprised questions on basic household characteristics, economic conditions (i.e., income and assets), living standards (e.g., housing and toilet), energy utilization, education (enrolment and study hours of children), health, and damage caused by natural and man-made disasters.

3.3 Statistical methods and variables

As per the non-experimental data collection explained above, we must rely on quasi-experimental methods to assess the impacts of the SHS. For example, Khandker *et al.* (2014) employ propensity score matching (PSM) to capture the effects of the SHS using cross-sectional data. However, a possible problem in using PSM is that the treatment variable (i.e., SHS use) is considered a binomial dummy variable that divides all samples into "SHS users" and "non-users." This means households that have utilized the SHS for both few months and many years are similarly classified as "SHS users" and accordingly, compared to non-users.

Since the introduction of SHS does not have immediate effects on household welfare, such a simple dichotomy leads to an underestimation of the impacts. While some variables such as fuel consumption may be immediately affected, outcomes related to education and health through changes in lifestyle are generally visible in the long run. This underestimation might be a serious problem in our sample. **Figure 2** shows that the duration of SHS use varies from 1 to 24 months among SHS users.

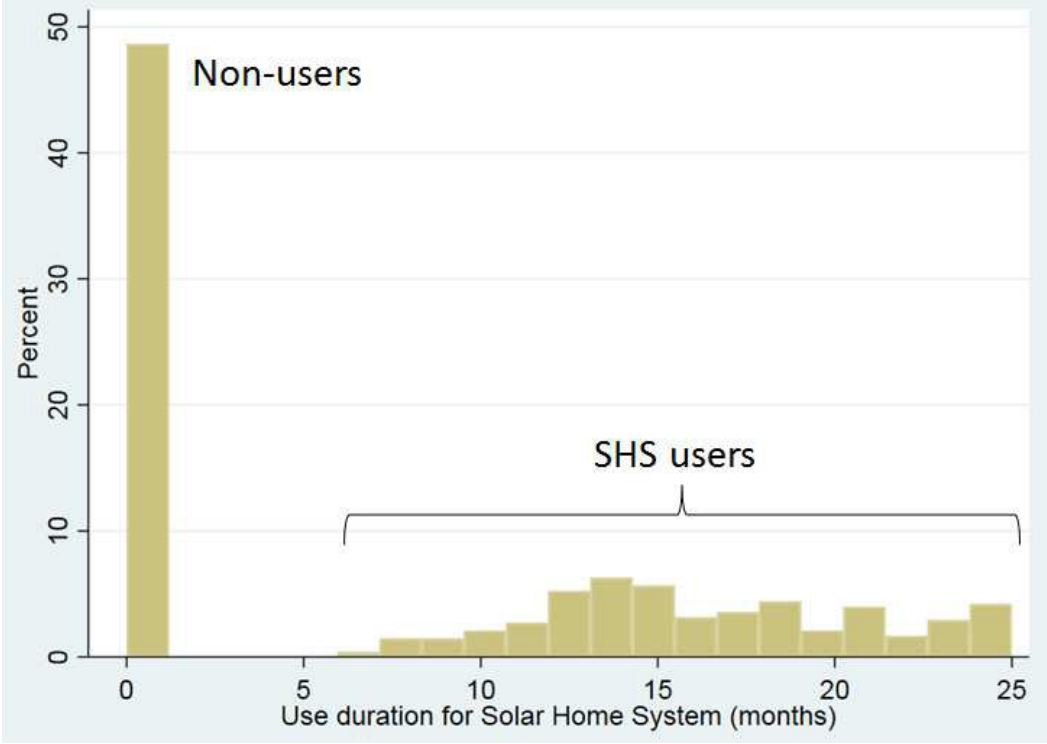

Figure 2. Distribution of use duration for solar home system (month)

Thus, to avoid this problem, we use another standard method, a household-level fixed-effects (FE) method, where the treatment variable is considered a continuous variable. The outcome equation can be expressed as

$$Y_{it} = \alpha + \beta d_{it} + \gamma' X_{it} + \theta_i + \varepsilon_{it},$$

where Y_{it} is the welfare variable for the i-th household in the t-th period; d_{it} is the duration of SHS use; X_{it} is a vector of household characteristics; θ_i is a vector of unobserved fixed determinants of household welfare; ε_{it} is an unobserved error term; α, β, and γ are the parameters to be estimated. The FE model can mitigate an endogeneity bias by controlling household's fixed effects (θ_i), although it is subject to the bias from unobserved household characteristics that vary over time.

We classified outcome variables that may be affected by the adoption of the SHS in the short term into six groups: (1) fuel use (2) education (children's study hours) (3) health (incidence of disease symptoms) (4) security (incidence of house burns and thefts) (5) income, and (6) expenditure. **Table 2** presents a detailed list with sample means and the differences between SHS users and non-users for 2012 and 2013. The comparison reveals that SHS users tend to consume less fuel, earn more income, and spend more on healthcare than non-users. On the other hand, there are minor differences between uses and non-users in the variables of education, security, and health conditions.

Table 3 lists explanatory variables that consist of the duration of SHS use, basic household characteristics, living environments including access to sanitary toilets and water sources, participation in NGOs, and damage caused by natural disasters (e.g., flood and drought). As explanatory variables in the regression of fuel use, education, and health, we add the unit prices of fuels (i.e., firewood, cow dung, and kerosene), child's attendance at schools, and possible factors of indoor air pollution, respectively. In the comparison with SHS users, non-users have younger household members, lower education levels, smaller land holdings and housing, longer duration of kerosene lamp use, and more smokers in the household.

Table 2. Summary statistics of outcome variables

	Unit	2012					2013				
		SHS users		Non-users		Difference	SHS users		Non-users		Difference
		N	Mean	N	Mean		N	Mean	N	Mean	
Fuel use (per capita per day)											
Firewood	Maund	191	0.75	286	0.88	−0.13***	245	0.80	232	0.95	−0.15***
Cow dung	Maund	191	0.19	286	0.20	−0.01	245	0.20	232	0.23	−0.04*
Kerosene	Liter	191	0.35	286	0.67	−0.33***	245	0.18	232	0.73	−0.55***
Education: children's study time at home (average hours per day)											
6–10 years	Hours	75	2.12	153	2.29	−0.16	91	2.31	116	2.41	−0.10
11–15 years	Hours	100	2.86	139	2.88	−0.01	117	3.05	124	3.21	−0.16
6–19 years	Hours	97	1.81	124	1.56	0.25	144	2.04	111	2.07	−0.03
Health: incidence of disease symptoms in any household member in the past 12 months											
Cough	Dummy	191	0.38	286	0.46	−0.08*	245	0.44	232	0.47	−0.03
Headache	Dummy	191	0.46	286	0.54	−0.08*	245	0.49	232	0.56	−0.07
Sore eyes	Dummy	191	0.35	286	0.34	0.00	245	0.35	232	0.36	−0.01
Skin burns	Dummy	191	0.08	286	0.07	0.01	245	0.09	232	0.08	0.01
Security: incidence of house burns and thefts in the past 12 months											
House burns	Dummy	191	0.000	286	0.003	−0.003	245	0.004	232	0.009	−0.005
Thefts	Dummy	191	0.016	286	0.010	0.005	245	0.029	232	0.013	0.016
Income (per capita per month)											
Total income	Taka	191	2,162.80	286	1,753.79	409.02***	245	2,359.14	232	1,834.42	524.72***
Farm income	Taka	191	280.20	286	200.04	80.17	245	286.85	232	210.23	76.62
Non-farm income	Taka	191	1,882.60	286	1,553.75	328.85**	245	2,072.29	232	1,624.19	448.10***
Expenditure (per capita per month)											
Total expenditure	Taka	191	1,967.55	286	1,923.58	43.97	245	2,309.77	232	2,173.31	136.45
Food	Taka	191	1,174.17	286	1,208.23	−34.05	245	1,380.75	232	1,335.47	45.28
Clothing	Taka	191	201.01	286	186.55	14.46	245	239.45	232	215.27	24.19**
Fuel	Taka	191	49.04	286	72.97	−23.93***	245	36.37	232	79.72	−43.35***
Healthcare	Taka	191	259.76	286	189.25	70.51***	245	281.98	232	224.17	57.81**
Education	Taka	191	269.69	286	241.74	27.95	245	340.26	232	285.01	55.25*

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 3. Summary statistics of explanatory variables

	Unit	2012					2013				
		SHS users		Non-users		Difference	SHS users		Non-users		Difference
		N	Mean	N	Mean		N	Mean	N	Mean	
Duration of SHS use	month	191	6.08	286	0.00	6.08***	245	16.36	232	0.00	16.36***
Household characteristics											
Household size	persons	191	4.45	286	4.35	0.09	245	4.48	232	4.26	0.22**
0–14 years	rate	191	0.26	286	0.32	−0.05***	245	0.24	232	0.30	−0.05***
15–64 years	rate	191	0.69	286	0.65	0.03*	245	0.70	232	0.68	0.02
65 years & above	rate	191	0.05	286	0.03	0.02**	245	0.06	232	0.03	0.03***
Member w/o formal education	rate	191	0.31	286	0.35	−0.04	245	0.31	232	0.36	−0.05*
Member w/ primary education	rate	191	0.27	286	0.32	−0.05*	245	0.27	232	0.33	−0.06**
Member w/ secondary education	rate	191	0.25	286	0.23	0.02	245	0.26	232	0.22	0.05**
Member with higher education	rate	191	0.17	286	0.10	0.06***	245	0.16	232	0.10	0.06***
Living environments											
Area of land owned	decimal	191	106.48	286	62.87	43.61***	245	104.49	232	54.56	49.93***
No. of house rooms	number	191	3.28	286	3.08	0.19**	245	3.37	232	3.03	0.34***
Access to sanitary toilets	dummy	191	0.73	286	0.73	−0.00	245	0.76	232	0.68	0.08*
Access to tube wells	dummy	191	1.00	286	0.99	0.01	245	1.00	232	1.00	0.00
Participation in NGO											
Grameen Bank	dummy	191	0.120	286	0.171	−0.051	245	0.180	232	0.207	−0.027
BRAC	dummy	191	0.037	286	0.028	0.009	245	0.037	232	0.047	−0.011
ASA	dummy	191	0.084	286	0.063	0.021	245	0.118	232	0.134	−0.015
Others	dummy	191	0.037	286	0.070	−0.033	245	0.053	232	0.108	−0.055**
Damage caused by disasters											
Flood	dummy	191	0.000	286	0.017	−0.017*	245	0.159	232	0.194	−0.035
Storm	dummy	191	0.000	286	0.010	−0.010	245	0.020	232	0.022	−0.001
Drought	dummy	191	0.042	286	0.049	−0.007	245	0.061	232	0.073	−0.012
Agricultural damages	dummy	191	0.058	286	0.059	−0.002	245	0.106	232	0.116	−0.010
Livestock deaths	dummy	191	0.037	286	0.035	0.002	245	0.057	232	0.078	−0.020
Unit price of fuel											
Firewood	Tk/maund	191	88.63	286	92.19	−3.56***	245	99.72	232	102.73	−3.01**
Cow dung	Tk/maund	191	70.13	286	53.76	16.37***	245	76.21	232	54.92	21.29***
Kerosene	Tk/liter	191	70.06	286	70.78	−0.72***	245	73.04	232	72.80	0.25
Child's attendance at schools											
6–10 years	days/week	75	4.95	153	5.22	−0.27	91	4.97	116	5.21	−0.24
11–15 years	days/week	100	5.32	139	5.18	0.13	117	5.10	124	5.44	−0.34
6–19 years	days/week	97	2.55	124	2.25	0.30	144	2.77	111	2.59	0.18
Possible factors of indoor-air-pollution											
Use of kerosene lamp	hours/day	191	1.58	286	3.24	−1.66***	245	0.77	232	3.51	−2.73***
Use of stove	hours/day	191	2.54	286	2.58	−0.04	245	2.69	232	2.77	−0.08
Smokers in the household	dummy	191	0.23	286	0.34	−0.11***	245	0.21	232	0.40	−0.19***

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4. Summary of impacts of solar home system

	Per capita fuel consumption			Education: study hours for children		
	Firewood	Cow dung	Kerosene	6–10 years	11–15 years	16–2 years
Duration of SHS use	0.000	−0.002**	−0.022***	0.015***	0.022***	0.004
	(0.001)	(0.001)	(0.002)	(0.005)	(0.006)	(0.006)
Sample size	477	477	477	207	241	255
R-squared	0.505	0.162	0.301	0.370	0.404	0.384

	Health: incidence of disease and injury				Security	
	Cough	Headache	Sore eyes	Skin burn	House burn	Theft
Duration of SHS use	0.002	−0.001	0.001	0.001	0.000	0.001
	(0.002)	(0.001)	(0.002)	(0.001)	(0.000)	(0.001)
Sample size	477	477	477	477	477	477
R-squared	0.084	0.075	0.072	0.057	0.025	0.075

	Per capita income (log)			Per capita consumption (log)					
	Total	Farm	Non-farm	Total	Food	Cloth	Energy	Healthcare	Education
Duration of SHS use	0.008***	0.004	0.009***	0.010***	0.011***	0.011***	-−.036***	0.001	0.016**
	(0.002)	(0.008)	(0.003)	(0.001)	(0.001)	(0.001)	(0.006)	(0.003)	(0.007)
Sample size	477	477	477	477	477	477	477	477	477
R-squared	0.079	0.038	0.075	0.507	0.518	0.330	0.177	0.047	0.067

Note: Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Detailed results with other control variables are presented in the Appendix.

4. Empirical Results

4.1 Main results

Table 4 summarizes the estimated impacts of the SHS on all outcome variables. The detailed regression tables for each outcome group are presented in the Appendix.

The results indicate the negative impacts of cow dung and kerosene on fuel consumption. More concretely, it is estimated that an additional month of SHS use contributes to a reduction in monthly consumption by 0.66 liter/person (or 2.96 liter/household for the average household size in our survey) for kerosene, and by 0.06 maund/person (i.e., 2.24 kg/person or 10.04 kg/household) for cow dung. This reduction in amounts is equivalent to 6% for kerosene and 1% for cow dung compared with the average of SHS users in 2012. In addition, the SHS positively impacts the study hours of children aged 6–15 years, but it has no statistically significant effect on children aged 16–21 years. For children aged 6–15 years among SHS users, the monthly study time at home is increased by 36 minutes, compared with non-users. These impacts on fuel consumption and education are consistent with the results of previous research (Khandker *et al.* 2014).

However, while Khandker *et al.* (2014) report improvements in health conditions among SHS users, we find no such impact on the incidence of diseases and injuries. Our finding is consistent with that of Kudo *et al.* (2017, forthcoming), who conducted an experimental study in northern Bangladesh and observed negligible impacts on health. As shown in the **Table A3**, **Appendix,** the use of a traditional cook stove with high levels of smoke emission is the most significant cause of cough, headache, and sore eyes. As the cook stove cannot be replaced by the SHS, the impacts of the SHS on health conditions are limited. In addition, in terms of security, no effect on the incidence of house burn and thefts can be observed.

On the other hand, the SHS contributes to an increase in income and expenditure. The estimate shows an additional month of SHS use increases non-farm and total income by approximately 1%. Although the size of the effect seems marginal, it may increase as the impact accumulates over time. In line with the increase in income, total expenditure grows by 1%. We also find changed in budget allocation: energy cost declines by 3.6% and expenditures on food, clothing, and education increase by more than 1%. It should be noted that some estimates for participation by microfinance institutions show positive effects on expenditure (**Table A6**)[1].

4.2 Robustness check for measurement errors

Because our survey is based on retrospective recall of respondents, there may be measurement errors in outcome and explanatory variables. In the case that the outcome variable includes measurement error, it is known that the ordinary least squares (OLS) estimators are still unbiased and consistent if the error is statistically independent of each explanatory variable, as is often assumed. However, measurement errors in explanatory

[1] We tried other specifications that additionally include the interaction term of the duration of SHS use and the dummy variable of the access to microfinance. However, we found that these coefficients of the interaction term for all outcomes are generally very small and not statistically significant. This may be because the SHS can be purchased in installments with relatively small payments, as explained in Section 2. In this scheme, customers may not need additional loans from microfinance institutions. If payment by installments is not allowed, then customers should prepare a large amount of money and depend on microfinance. In such situations, coefficients of the interaction term might become important.

variables can make OLS estimators biased and inconsistent. In our context, the most important explanatory variable is the duration of SHS use. For SHS users, some respondents might report the duration as few months more or less than actual duration due to lapse of memory.

More specifically, our two-period FE model is equivalent to the first difference (FD) model estimated by OLS:

$$\Delta Y_i = \beta \Delta d_i + \gamma' \Delta X_i + \Delta \varepsilon_i,$$

where Δ indicates the difference of each variable between the two periods. The measurement error in the duration of SHS is defined as the difference between the actual duration (Δd_i) and the reported one (Δd_i^*):

$$\mathrm{e}_i = \Delta d_i^* - \Delta d_i.$$

By substitution of the equation into the FD model, we get

$$\Delta Y_i = \beta \Delta d_i^* + \gamma' \Delta X_i + (\Delta \varepsilon_i - \beta e_i).$$

If Δd_i^* and e_i are not correlated, OLS estimators are still unbiased and consistent. However, under the classical errors in variables assumption, $\mathrm{Cov}(\Delta d_i, \mathrm{e}_i) = 0$, Δd_i^* and e_i must be correlated, which causes biases and inconsistencies. One standard way to mitigate the biases is the errors-in-variables (EIV) regression model[2] that adjusts estimators based on the reliability:

$$r = 1 - \frac{Var(e_i)}{Var(\Delta d_i)}.$$

The reliability takes one if there is no measurement error in the variable, and it becomes small if the error is large. Although the true reliability is not known in our analysis, we can check the robustness of the results in **Table 4** by setting various values for the reliability.

Table 5 shows the results[3] for three cases wherein the reliability of the duration of SHS use is set as 0.9, 0.8, and 0.7, respectively. In general, coefficients become larger when the reliability is set lower, which in known as "attenuation bias" with measurement errors. We can confirm that all findings in the previous section (**Table 4**) still hold even in the row reliability of 0.7. These results support the view that our main results are robust against measurement errors.

[2] In a simple model of $\mathrm{y} = \mathrm{X}\beta + \varepsilon$ with measurement error $\mathrm{e} = X^* - X$, estimators of the EIV regression model can be obtained as $(\mathrm{X}'\mathrm{X} - \mathrm{C})\mathrm{X}'\mathrm{y}$, where C is a diagonal matrix with elements $\mathrm{N}(1 - r_k)Var(x_k)$.

[3] The results for education (study hours for children) are not reported here because we could not calculate the EIV estimators due to the limitation of sample size.

Table 5. Robustness check: Errors-in-variables estimators for impacts of the duration of SHS use

Category	Outcome Variables	Reliability = 0.9			Reliability = 0.8			Reliability = 0.7		
		Coeff.	S.E.	p-value	Coeff.	S.E.	p-value	Coeff.	S.E.	p-value
Fuel consumption	Firewood	0.000	0.001	0.982	0.000	0.001	0.982	0.000	0.001	0.982
	Cow dung	-0.002	0.001	0.056	-0.002	0.001	0.056	-0.002	0.001	0.056
	Kerosene	-0.024	0.002	0.000	-0.027	0.002	0.000	-0.031	0.003	0.000
Income	Total income	0.008	0.003	0.005	0.009	0.003	0.004	0.009	0.003	0.004
	Farm income	0.004	0.009	0.672	0.004	0.010	0.672	0.004	0.010	0.672
	Non-farm income	0.010	0.004	0.006	0.011	0.004	0.006	0.012	0.004	0.006
Expenditure	Total expenditure	0.011	0.001	0.000	0.012	0.001	0.000	0.013	0.001	0.000
	Food	0.012	0.001	0.000	0.012	0.001	0.000	0.013	0.001	0.000
	Clothing	0.012	0.002	0.000	0.013	0.002	0.000	0.014	0.002	0.000
	Fuel	-0.039	0.005	0.000	-0.041	0.006	0.000	-0.045	0.006	0.000
	Healthcare	0.002	0.003	0.653	0.002	0.004	0.653	0.002	0.004	0.653
	Education	0.018	0.006	0.006	0.019	0.007	0.006	0.020	0.007	0.006
Health	Cough	0.002	0.002	0.260	0.002	0.002	0.260	0.002	0.002	0.260
	Headache	-0.001	0.001	0.403	-0.001	0.002	0.402	-0.002	0.002	0.402
	Sore eyes	0.001	0.002	0.720	0.001	0.002	0.720	0.001	0.002	0.720
	Skin burns	0.001	0.001	0.155	0.002	0.001	0.155	0.002	0.001	0.155
Security	House burns	0.000	0.001	0.474	0.000	0.001	0.474	0.001	0.001	0.474
	Thefts	0.001	0.001	0.377	0.001	0.001	0.377	0.001	0.001	0.376

5. Conclusions

In this study, we assessed the multidimensional impacts of the SHS on monetary outcomes and the non-monetary aspects of welfare such as education, health, and security by conducting a field survey in Bangladesh. The estimation of the household fixed effect model shows that the SHS contributes to reduced fuel consumption; extended study hours for children; and increased non-farm income and expenditures on food, clothing, and education. These results support the view that the SHS has multiple positive impacts on certain components of the MPI. However, no improvement in health and security was confirmed in our data. Based on the evidence that diseases are mainly caused by the use of a traditional cook stove, an improved cook stove (ICS) is a more effective device than the SHS to improve health conditions. In terms of security, our estimation may face the lack of statistical power because the frequencies of house burns and thefts are rare in the restricted sample size. Thus, a large-scale survey on access to electricity through not only the SHS but also the grid system is warranted to assess the impacts on household and community security. Finally, because our sample focuses on only the Barisal division, it should be noted that there is a limitation in generalizing our findings to other regions of Bangladesh. A nationally representative survey is needed to confirm the external validity to other regions.

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Appendix

Table A1. Impacts on per capita fuel consumption

	Per capita fuel consumption		
	Firewood	Cow dung	Kerosene
Duration of SHS use	0.000	−0.002**	−0.022***
	(0.001)	(0.001)	(0.002)
Household size	−0.322***	−0.034*	−0.172***
	(0.031)	(0.020)	(0.049)
Rate for 0–14 years olds	−0.017	0.086*	0.167
	(0.055)	(0.051)	(0.135)
Rate for 65 years olds & above	−0.056	0.201	−0.082
	(0.079)	(0.167)	(0.417)
Rate for primary education	0.097	0.043	−0.075
	(0.094)	(0.035)	(0.155)
Rate for secondary education	−0.002	−0.062	−0.160
	(0.098)	(0.068)	(0.178)
Rate for higher education	0.093	0.048	0.199
	(0.133)	(0.075)	(0.234)
Log of per capita income	−0.001	0.005	−0.020
	(0.007)	(0.008)	(0.020)
Area of land owned	−0.001**	−0.001***	−0.003*
	(0.000)	(0.000)	(0.002)
No. of house rooms	0.051***	0.053***	0.077*
	(0.018)	(0.017)	(0.040)
Access to sanitary toilet	0.065***	0.009	0.215
	(0.022)	(0.032)	(0.131)
Access to tube well	0.055*	0.006	0.155
	(0.029)	(0.035)	(0.143)
Member of Grameen Bank	0.027	0.013	−0.042
	(0.020)	(0.017)	(0.036)
Membership of BRAC	−0.005	−0.029*	−0.090
	(0.020)	(0.016)	(0.056)
Membership of ASA	−0.008	−0.010	−0.068
	(0.017)	(0.010)	(0.042)
Membership of other NGOs	−0.015	0.007	0.071*
	(0.022)	(0.013)	(0.041)
Damage by flood	−0.027***	0.002	0.035
	(0.010)	(0.009)	(0.035)
Damage by storm	0.004	0.026	−0.024
	(0.036)	(0.033)	(0.049)
Damage by drought	−0.012	−0.024	−0.038
	(0.013)	(0.022)	(0.099)
Agricultural damages	−0.018	−0.011	−0.007
	(0.012)	(0.009)	(0.062)
Damage to livestock (deaths)	−0.008	0.014	0.002
	(0.013)	(0.011)	(0.050)
Unit price of firewood	0.003***	0.001**	0.004***
	(0.001)	(0.001)	(0.001)
Unit price of cow dung	0.001	0.003***	−0.002
	(0.001)	(0.001)	(0.001)
Unit price of kerosene	0.002	−0.000	0.006
	(0.002)	(0.001)	(0.005)
Constant term	1.497***	−0.093	0.490
	(0.199)	(0.153)	(0.463)
Sample size	954	954	954
R-squared	0.505	0.162	0.301

Note: Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A2. Impacts on study hours for children

	Children's study hours		
	6–10 years	11–15 years	16–21 years
Duration of SHS use	0.015***	0.022***	0.004
	(0.005)	(0.006)	(0.006)
Household size	−0.288**	−0.215	0.025
	(0.146)	(0.203)	(0.191)
Rate for 0–14 years olds	−0.457	−0.633*	−1.515
	(0.637)	(0.329)	(1.179)
Rate for 65 years olds & above	1.297	0.860	−0.115
	(1.436)	(1.310)	(1.575)
Rate for primary education	0.910	−0.458	−1.333*
	(0.587)	(0.975)	(0.680)
Rate for secondary education	1.449*	−0.061	−0.820
	(0.752)	(0.952)	(1.412)
Rate for higher education	0.925	−0.134	−0.036
	(0.809)	(1.515)	(1.228)
Log of per capita income	−0.055*	0.027	0.029
	(0.031)	(0.079)	(0.065)
Area of land owned	0.003	0.003**	−0.002
	(0.003)	(0.001)	(0.001)
No. of house rooms	0.278	0.263*	0.126
	(0.249)	(0.149)	(0.130)
Access to sanitary toilet	−0.978***	−0.994***	0.197
	(0.140)	(0.151)	(0.295)
Access to tube well	−0.948***	0.000	0.000
	(0.199)	(.)	(.)
Member of Grameen Bank	0.051	−0.209	0.446*
	(0.105)	(0.156)	(0.235)
Membership of BRAC	0.100	−0.280**	0.187
	(0.193)	(0.139)	(0.279)
Membership of ASA	0.167	0.112	−0.404
	(0.137)	(0.163)	(0.285)
Membership of other NGOs	−0.278	0.006	−0.124
	(0.193)	(0.151)	(0.203)
Damage by flood	0.116	0.162	0.067
	(0.124)	(0.123)	(0.154)
Damage by storm	0.007	−0.265	0.983***
	(0.207)	(0.266)	(0.352)
Damage by drought	0.164	0.344	0.440
	(0.172)	(0.213)	(0.324)
Agricultural damages	0.046	−0.035	−0.277
	(0.146)	(0.200)	(0.291)
Damage to livestock (deaths)	−0.004	0.131	0.141
	(0.178)	(0.219)	(0.468)
Attendance rate: 6–10 years	0.377***		
	(0.052)		
Attendance rate: 11–15 years		0.439***	
		(0.051)	
Attendance rate: 16–21 years			0.518***
			(0.106)
Constant term	2.027	1.453	0.521
	(1.254)	(1.607)	(1.249)
Sample size	207	241	255
R-squared	0.370	0.404	0.384

Note: Robust standard errors are in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1.

Table A3. Impacts on incidence of disease and injury

	Incidence of disease and injury			
	Cough	Headache	Sore eyes	Skin burn
Duration of SHS use	0.002	−0.001	0.001	0.001
	(0.002)	(0.001)	(0.002)	(0.001)
Household size	−0.014	−0.011	−0.006	0.013
	(0.013)	(0.013)	(0.013)	(0.012)
Rate for 0–14 years olds	−0.035	−0.096	−0.028	0.007
	(0.088)	(0.142)	(0.099)	(0.019)
Rate for 65 years olds & above	−0.073	0.004	−0.055	−0.029
	(0.075)	(0.074)	(0.081)	(0.026)
Rate for primary education	−0.204	−0.222*	−0.036	−0.134
	(0.138)	(0.130)	(0.096)	(0.112)
Rate for secondary education	0.067	−0.008	0.077	−0.279
	(0.188)	(0.125)	(0.150)	(0.248)
Rate for higher education	0.094	0.170	−0.202	−0.075
	(0.169)	(0.165)	(0.213)	(0.115)
Log of per capita income	−0.002	−0.002	−0.011	0.009
	(0.008)	(0.007)	(0.013)	(0.008)
Area of land owned	0.000	−0.000	0.000	−0.000
	(0.001)	(0.001)	(0.000)	(0.000)
No. of house rooms	−0.006	0.026	0.011	−0.022
	(0.027)	(0.056)	(0.046)	(0.017)
Access to sanitary toilet	−0.142	0.118	−0.036	0.162
	(0.141)	(0.142)	(0.193)	(0.136)
Access to tube well	−0.275*	0.018	−0.060	0.190
	(0.163)	(0.159)	(0.205)	(0.140)
Member of Grameen Bank	−0.066*	−0.014	−0.068	0.036
	(0.037)	(0.012)	(0.050)	(0.034)
Membership of BRAC	−0.124	−0.025	0.070	0.010
	(0.090)	(0.016)	(0.095)	(0.013)
Membership of ASA	0.090*	0.051	−0.089*	−0.011
	(0.053)	(0.045)	(0.049)	(0.052)
Membership of other NGOs	0.016	−0.055*	0.068	−0.040
	(0.032)	(0.032)	(0.052)	(0.030)
Damage by flood	0.029	0.042*	0.018	0.003
	(0.023)	(0.024)	(0.026)	(0.016)
Damage by storm	−0.004	−0.003	0.000	−0.007
	(0.014)	(0.010)	(0.016)	(0.010)
Damage by drought	−0.004	−0.008	−0.008	−0.024
	(0.017)	(0.011)	(0.040)	(0.020)
Agricultural damages	−0.019	−0.010	−0.035	0.029
	(0.015)	(0.010)	(0.028)	(0.032)
Damage to livestock (deaths)	−0.012	−0.014	0.014	−0.000
	(0.014)	(0.011)	(0.039)	(0.011)
Hours of kerosene lamp use	−0.002	−0.005	0.008	0.004
	(0.007)	(0.006)	(0.007)	(0.004)
Hours of stove use	0.057**	0.069**	0.070**	−0.007
	(0.027)	(0.031)	(0.033)	(0.006)
Smokers in the household	0.067	0.087	−0.046	0.010
	(0.077)	(0.076)	(0.039)	(0.014)
Constant term	0.783***	0.285	0.332	−0.143
	(0.239)	(0.262)	(0.279)	(0.199)
Sample size	477	477	477	477
R-squared	0.084	0.075	0.072	0.057

Note: Robust standard errors are in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1.

Table A4. Impacts on incidence of accidents

	Incidence of accidents	
	House burn	Theft
Duration of SHS use	0.000	0.001
	(0.000)	(0.001)
Household size	−0.002	−0.037
	(0.006)	(0.037)
Rate for 0–14 years olds	0.008	−0.190*
	(0.015)	(0.108)
Rate for ages 65 years olds & above	−0.016	−0.127
	(0.028)	(0.082)
Rate for primary education	0.110	0.120
	(0.121)	(0.105)
Rate for secondary education	0.070	−0.173
	(0.089)	(0.174)
Rate for higher education	0.025	0.045
	(0.061)	(0.094)
Log of per capita income	−0.011	0.003
	(0.013)	(0.005)
Area of land owned	0.000	−0.000
	(0.000)	(0.000)
No. of house rooms	−0.001	−0.002
	(0.004)	(0.008)
Access to sanitary toilet	−0.007	−0.005
	(0.010)	(0.013)
Access to tube well	−0.010	−0.018
	(0.010)	(0.014)
Member of Grameen Bank	−0.004	−0.013
	(0.005)	(0.010)
Membership of BRAC	−0.007	−0.012
	(0.006)	(0.011)
Membership of ASA	0.030	−0.015
	(0.034)	(0.011)
Membership of other NGOs	0.002	−0.042
	(0.006)	(0.035)
Damage by flood	−0.006	0.028
	(0.004)	(0.020)
Damage by storm	−0.007	0.094
	(0.010)	(0.092)
Damage by drought	0.001	−0.017
	(0.003)	(0.021)
Agricultural damages	−0.003	0.019
	(0.005)	(0.022)
Damage to livestock (deaths)	0.026	0.017
	(0.033)	(0.026)
Constant term	0.050	0.252
	(0.130)	(0.212)
Sample size	477	477
R-squared	0.025	0.075

Note: Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A5. Impacts on per capita income (log)

	Per capita income (log)		
	Total	Farm	Non-farm
Duration of SHS use	0.008***	0.004	0.009***
	(0.002)	(0.008)	(0.003)
Household size	−0.330***	0.185	−0.324***
	(0.051)	(0.235)	(0.054)
Rate for 0–14 years olds	−0.288	−0.640	−0.057
	(0.539)	(0.452)	(0.556)
Rate for 65 years olds & above	0.305*	0.119	0.106
	(0.156)	(0.505)	(0.181)
Rate for primary education	0.000	0.473	−0.093
	(0.155)	(1.009)	(0.155)
Rate for secondary education	−0.345*	−1.025	−0.428**
	(0.199)	(1.527)	(0.213)
Rate for higher education	0.050	0.625	0.067
	(0.207)	(0.955)	(0.229)
Area of land owned	0.002	−0.010	0.002**
	(0.001)	(0.010)	(0.001)
No. of house rooms	0.060	0.088	−0.020
	(0.045)	(0.432)	(0.054)
Access to sanitary toilet	−0.046	−0.744	0.000
	(0.093)	(0.497)	(0.108)
Access to tube well	0.129	−0.417	0.360
	(0.122)	(0.520)	(0.318)
Member of Grameen Bank	0.058	0.228	0.249
	(0.068)	(0.231)	(0.246)
Membership of BRAC	0.025	0.536	0.065
	(0.071)	(0.560)	(0.073)
Membership of ASA	0.083***	0.364	0.019
	(0.032)	(0.259)	(0.043)
Membership of other NGOs	0.094	−0.101	0.309
	(0.080)	(0.358)	(0.302)
Damage by flood	−0.024	0.009	−0.034
	(0.041)	(0.106)	(0.049)
Damage by storm	0.032	−0.256	0.027
	(0.051)	(0.648)	(0.073)
Damage by drought	0.100	0.120	0.032
	(0.070)	(0.471)	(0.064)
Agricultural damages	−0.089	−0.466**	−0.034
	(0.064)	(0.185)	(0.067)
Damage to livestock (deaths)	−0.022	0.176	0.003
	(0.054)	(0.305)	(0.032)
Constant term	8.552***	2.869	7.709***
	(0.375)	(2.407)	(0.545)
Sample size	477	477	477
R-squared	0.079	0.038	0.075

Note: Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A6. Impacts on per capita consumption (log)

	Per capita consumption (log)					
	Total	Food	Cloth	Energy	Health	Education
Duration of SHS use	0.010***	0.011***	0.011***	−0.036***	0.001	0.016**
	(0.001)	(0.001)	(0.001)	(0.006)	(0.003)	(0.007)
Household size	−0.309***	−0.319***	−0.314***	−0.198	−0.230***	−0.083
	(0.035)	(0.034)	(0.054)	(0.178)	(0.058)	(0.129)
Rate for 0–14 years olds	−0.199**	−0.211***	−0.186*	1.191*	−0.384*	−0.194
	(0.081)	(0.070)	(0.109)	(0.614)	(0.204)	(0.276)
Rate for 65 years olds & above	0.121	0.161	0.015	1.360	0.288	−0.138
	(0.149)	(0.166)	(0.191)	(0.968)	(0.314)	(0.340)
Rate for primary education	0.159	0.157	0.173	−0.073	−0.243	1.762*
	(0.106)	(0.097)	(0.154)	(0.328)	(0.408)	(0.922)
Rate for secondary education	0.189	0.214*	−0.032	−0.520	0.051	1.127
	(0.131)	(0.120)	(0.192)	(0.424)	(0.346)	(0.755)
Rate for higher education	0.301*	0.281*	0.345	0.790	0.002	1.070
	(0.179)	(0.160)	(0.302)	(0.612)	(0.366)	(0.701)
Log of per capita income	0.035	0.025	0.050	−0.066	−0.013	0.054
	(0.038)	(0.028)	(0.034)	(0.053)	(0.046)	(0.078)
Area of land owned	−0.001***	−0.001***	−0.001	−0.008**	−0.001	−0.002
	(0.000)	(0.000)	(0.002)	(0.003)	(0.001)	(0.002)
No. of house rooms	0.119***	0.083***	0.251***	0.582***	−0.044	0.079
	(0.027)	(0.020)	(0.089)	(0.182)	(0.097)	(0.132)
Access to sanitary toilet	−0.105*	−0.095	−0.892	0.113	0.436	0.472
	(0.059)	(0.064)	(0.654)	(0.296)	(0.646)	(0.564)
Access to tube well	−0.048	−0.051	−0.808	0.025	0.408	0.671
	(0.064)	(0.069)	(0.665)	(0.339)	(0.658)	(0.596)
Member of Grameen	0.049**	0.039*	0.081**	−0.177	−0.036	0.189
	(0.024)	(0.021)	(0.041)	(0.164)	(0.046)	(0.170)
Membership of BRAC	0.057	0.028	−0.031	−0.140	0.054	0.063
	(0.048)	(0.035)	(0.063)	(0.202)	(0.064)	(0.080)
Membership of ASA	0.036	0.014	0.078***	−0.167	0.143**	0.211
	(0.025)	(0.022)	(0.027)	(0.137)	(0.063)	(0.208)
Membership of others	0.062**	0.038	0.019	0.222***	0.102	0.369**
	(0.028)	(0.025)	(0.051)	(0.084)	(0.114)	(0.179)
Damage by flood	0.028**	0.004	0.017	0.096	0.070*	0.015
	(0.012)	(0.011)	(0.022)	(0.070)	(0.036)	(0.114)
Damage by storm	0.065*	0.038	0.036	−0.017	0.248*	0.209
	(0.039)	(0.042)	(0.053)	(0.157)	(0.126)	(0.333)
Damage by drought	0.028	0.018	0.064	0.199	0.009	−0.048
	(0.037)	(0.032)	(0.050)	(0.127)	(0.150)	(0.091)
Agricultural damages	−0.005	−0.023	−0.013	−0.136	0.115	0.081
	(0.023)	(0.021)	(0.043)	(0.142)	(0.071)	(0.083)
Damage to livestock (deaths)	0.003	0.014	0.038	0.153	−0.039	−0.003
	(0.028)	(0.024)	(0.044)	(0.159)	(0.117)	(0.133)
Constant term	8.345***	8.049***	6.821***	3.544***	4.872***	2.502*
	(0.393)	(0.314)	(0.997)	(1.200)	(1.024)	(1.324)
Sample size	477	477	477	477	477	477
R-squared	0.507	0.518	0.330	0.177	0.047	0.067

Note: Robust standard errors are in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1.