Climate Variability, Livelihood Diversification, and Household Food Security in Bangladesh

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Abstract

Climate variability has become much more obvious as a result of global climate change. Livelihood diversification including farm and income diversification is one of the most remarkable strategies to manage risk and cope with economic and climate shocks in order to improve rural livelihood. We investigate the empirical linkages among climate variability, livelihood diversification, and household food security, exploiting three waves of nationally representative rural household panel data merged with granular climate data in Bangladesh. Using control function approach and IV regression to control for possible endogeneity of livelihood diversification decision, we find that climate variability affects both livelihood diversification and household food security, and income diversification improves household food security. In particular, the impact of income diversification on food security is greater for the poorer households. The findings, therefore, highlight the pro-poor impact of diversification strategies in rural South Asia contexts, and suggests the need for diversification interventions targeting the rural poor, in terms of socio-economic factors, institutional conditions, and infrastructure.

Keywords: Livelihood diversification, Climate shocks, Adaptation, Food security, Heterogeneity, Bangladesh

JEL classification: O13, Q01, Q12, Q54, Q56

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Introduction

Climate variability has become much more obvious as a result of global climate change. The potential impact of climate change on agricultural production, yield, and productivity is also an additional strain on the global food system (Knox et al., 2012; Hossain et al., 2018; Rahman and Anik, 2020; Miller et al., 2021). As a result, farm household' welfare become unstable (Carpena, 2019). In developing countries, smallholder farmers are particularly vulnerable to shocks including climate shocks to their agricultural system owing to their high dependence on agriculture for livelihoods, chronic food insecurity, physical isolation, and lack of access to formal safety nets (Harvey et al., 2014, Chuang, 2019). Therefore, adapting to intense climate variability is imperative to sustain farmers' livelihood and food security in these countries.

Livelihood diversification, which is defined as the process by which rural families construct a diverse portfolio of activities and social support capabilities in their struggle for survival and in order to improve their standards of living (Ellis, 1998), is one of the most remarkable characteristics of rural livelihood (Gautam and Andersen, 2016). Diversification is a viable strategy to manage risk, cope with economic and climate shocks, or escape from agriculture in stagnation or in secular decline (Zhao and Barry, 2014). Diversification of on-farm production systems and livelihood supporting sources can help to spread the risk of climate-induced production and market uncertainty (Asfaw et al., 2019). Furthermore, through both subsistence- and income-generating pathways, diversification of agricultural production systems may improve dietary quality as well as having environmental benefits. Therefore, diversification in its various forms is an important strategy for improving diets and nutrition outcomes in low- and middle-income countries (Di Falco and Chavas, 2009; Jones, 2017), which thus gives an incentive for households to diversify (Chavas and Di Falco, 2012).

In this article, we look at the drivers of livelihood diversification with an emphasis on the role of climate change and the impact of livelihood diversification on household food security outcomes in Bangladesh. To this end, we make use of three waves of nationally representative household survey data in Bangladesh, combining geo-referenced historical climate data. We look at two research questions. First, we study how farmers respond to climate variability through livelihood diversification. Second, we identify, to what extent, livelihood diversification improves household food security. Then we investigate whether there are any heterogeneous impacts of livelihood diversification on household food security, varying across the per capita food expenditure.

The relationship among climate variability, livelihood diversification and household food security has been subject to substantial scrutiny in the past. Asfaw et al. (2018, 2019) found that exposure to extreme climate events is positively associated with either crop or income diversification. Moreover, Owusu et al. (2011), Olale and Henson (2013), and Bozzola and Smale (2020) found that livelihood diversification and off-farm income increases income, reduce the poverty, improve food security, and make lower income groups to move out of poverty trap. In addition, Babatunde and Qaim (2010), Islam et al. (2018), and Dedehouanou and McPeak (2020) found that livelihood diversification improves calorie supply, dietary diversity, and food expenditure since farmers with greater income diversification is more likely to obtain adequate income (Amfo et al., 2021). A systematic summary of the literature on income diversification and livelihoods in Rural Africa by Barrett et al. (2001b) pinpointed to a positive relationship between nonfarm income and household welfare. Barrett et al. (2001b) also showed the existence of substantial entry or mobility barriers to high return niches within the rural nonfarm economy, and the positive relationship between nonfarm income diversification and growth in earnings and consumption.

In Bangladesh, households with small farm size dominated the agriculture sector (Moniruzzaman, 2015), indicating that the livelihood of many people in the country is vulnerable to climate variability. Significant progress in reducing poverty and improving malnutrition in the country has been made over the past two decades, yet many indicators of food security and malnutrition remain high (Islam et al., 2018). Bangladesh is one of the most vulnerable countries to climate risks, it is also disaster prone because of its geophysical setting and projected future changes in climate (Ruane et al., 2013; Sarker et al., 2020). Toward poverty reduction and food security improvement, farm and income diversification are crucial under climate change in Bangladesh. Mishra et al. (2015) showed the income of rural households is well diversified between agricultural and non-agricultural sources in Bangladesh, and off-farm income increased the food expenditures of rural households. However, attempts to investigate the impact of livelihood diversification on household food security, while controlling for climatic effect has been sparse.

Our study adds to the slim body of livelihood and crop diversification, climate change and food security literature by using three waves nationally rural representative panel data combining with longitudinal historical climate data in Bangladesh and present empirical evidence about the relationship among climate variability, livelihood diversification, and household food security. To the best of our knowledge, most of studies assessed these linkages in African settings while important knowledge gaps remain in understanding the impacts of climate variability on smallholder systems in South Asia. Furthermore, this study explicitly tests for the presence of heterogeneous impact of livelihood diversification across per capita food expenditure distributions of rural households. By doing so, important policy implications regarding the distributional effects of diversification can be inferred from the present study..

The remainder of this article is organized as follows. In Section 2, we explain our conceptual framework, describing the data, key variables which are of interests, and the empirical strategy used in the analysis. Section 3 discusses the results and robustness checks. Finally, Section 4 provides concluding remarks, and policy implications.

Research methods and data

Conceptual framework

The conceptual framework in this study is based on the sustainable livelihood framework in Ellis (2000) which is developed and adopted by relevant literature by Ellis (1998), Asfaw et al., (2019), and Gao and Mills (2018). By considering livelihood diversification as the strategy for smallholder households to manage adverse impacts on food security caused by extreme climatic events, uncertain agricultural production and unexpected market shocks (Barrett et al., 2001b; Asfaw et al., 2019), this study investigates the impact of diversification on rural household' food security which is measured by the household dietary diversity (HDDS) and per capita food expenditure.

We assume that climate variability affects household food security while livelihood diversification improves household security by mitigating its effect and increasing the resilience. It is worth noting that multiple motives prompt households and individuals to diversify assets, incomes, and activities (Barrett et al., 2001b). Multiple motives are push factors which is risk reduction, and pull factors which are realization of strategic complementarities between activities (Barrett et al., 2001b). While the ex-ante diversification can be planned so that an expected potential challenge can be faced, the ex-post diversification represents a feedback action to an unanticipated shock shrinking the household food security. The conceptual model is specified as

$$\mathrm{H} = \mathrm{f}[\mathrm{D}(\mathrm{C}, \mathrm{X}), \mathrm{C}; \mathrm{Z}] \tag{1}$$

where H is household food security, D is diversification, C is climate variability, X is covariates, Z is a unobserved factor. We expect to observe

$$\frac{\partial \mathrm{H}}{\partial \mathrm{C}} = \frac{\partial \mathrm{f}(\mathrm{D})}{\partial \mathrm{D}} \frac{\partial \mathrm{D}}{\partial \mathrm{C}} + \frac{\partial \mathrm{F}(\mathrm{c})}{\partial \mathrm{C}} \tag{2}$$

$$\frac{\partial \mathrm{H}}{\partial \mathrm{D}} > 0 \tag{3}$$

Climate variability is hypothesized to affect and deteriorate household welfare as Porter (2012) found that less rainfall shocks in the form of extreme low rainfall relative to local norms can cause significant reductions in consumption. Then, $\partial H/\partial C$ would be represented in Equation 2. On the other hand, livelihood diversification works as climate change adaptation strategies, mitigating the negative effect of climate risks (Gao and Mills, 2018; Barrett et al., 2001b; Chen and Gong, 2021). Therefore, we hypothesize that $\partial H/\partial D > 0$ in Equation 3, in terms of the

effect of livelihood diversification. Otherwise, the climate variability will generate fluctuations in household food security. As we mentioned above, climate variability directly affects household food security, and indirectly affects it through livelihood diversification simultaneously.

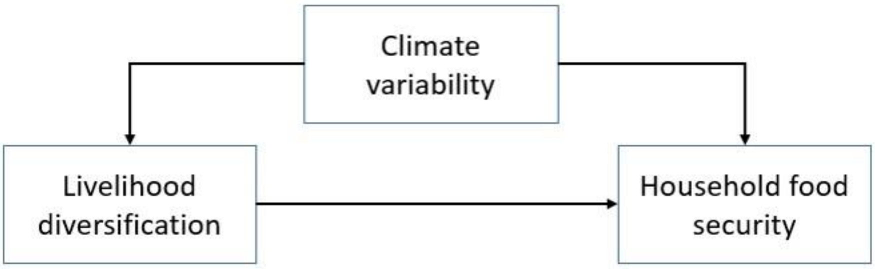

Figure 1 Conceptual framework for identifying effective livelihood diversification

Data

Household data: The data for this study is drawn from a recently collected three-round panel survey, the Bangladesh Integrated Household Survey (BIHS), which was designed and supervised by researchers at the International Food Policy Research Institute (IFPRI) in 2011/2012, 2015, and 2018/2019 (IFPRI, 2013; IFPRI, 2016; IFPRI, 2020), and (Ahmed and Tauseef, 2021). The sample is representative of rural areas of the seven administrative division of the county (Islam et al., 2018; Ahmed and Tauseef, 2021). BIHS used a stratified sampling procedure in two stages. The sample design of the BIHS followed a stratified sampling in two stages—selection of primary sampling units (PSUs) and selection of households within each PSU—using the sampling frame developed from the community series of the 2001 Population and Housing Census of Bangladesh (Ahmed and Tauseef, 2021). The total sample size in the first wave is 5503 households in 275 PSUs which are allocated among seven divisions Ahmed and Tauseef (2021). Sampling weights were adjusted based on the latest population census of 2011 and subsequently updated for each round of survey to retain the Representative of the sample at the rural national level and each of the

seven administrative divisions of the country. Taking attrition and split households into account, the total sample size in the second wave is 5447 households and the third wave is 5605 (Ahmed and Tauseef, 2021). Because our analysis focuses on the medium-term effects of livelihood diversification, we select the sub-sample of households observed across multiple waves, removing households who have missing values. The data includes household socio-economic, institutional, and agronomic information. An overall of descriptive statistics is presented in Table 2.

Weather data: The weather data from Bangladesh Meteorology Department includes monthly precipitation and temperature from 1992 March to 2019 February on 0.5-degree latitude by 0.5-degree longitude global grid. Bangladesh has four seasons (Bangladesh Meteorology Department, 2013; Kabir et al., 2017): summer (pre-monsoon) from March to

May, rainy monsoon season distinguished by heavy seasonal rainfall, high temperatures, and high humidity (Hossain et al., 2018) which lasts from June to September, autumn (post-monsoon), and winter season from December to February showed in Table 1. Then, we construct rainfall shock and temperature shock variables of four seasons using historical data§. An overall of climate variables is presented in Table 2.

To estimate the impact of climate variability, we matched the aggregated weather data with districts which consists of 64 districts in this study because rainfall and temperature are aggregate shocks.

Calculation and description of key outcome and explanatory variables

1.Diversification indices

We introduce an income diversification index, transformed from Simpson index which are usually used to indicate a diversity (Asfaw et al., 2019). The index is written as below:

$$\text{Simpson} = 1 - \sum_{k=1}^{n} \left[\frac{f_k}{f}\right]^2$$

where f_k is income (farmland area) share for income (crop) k, and f is total income (farmland area). A highly diversified household has an index close to 1, while a fully specialized one has an index of 0. Moreover, we divided income sources into farm income, farm wage, non-farm wage, non-farm self-employment, and non-earned income such as remittance and social network program transfer, etc., following Khandker (2012). Figure 2 shows that the share of non-farm income is around 50 % of total income of households. Figure 3 shows the density distributions of farm and income diversification index by waves. From Figure 3, around one-third of the farmers specialize in their farm income, while the rest of the farm households have multiple farm income sources. The diversification indices are censored at 0 but they are a corner at zero for specific households.

To test the robustness our main indicators of livelihood diversification, we use alternative indicators of livelihood diversification, which is Shannon diversification index as best known index with Simpson index (Duelli and Obrist, 2003). The index is derived as follows.

$$\text{Shannon} = -\sum p_i \times \ln(p_i)$$

where p_i is the area share for crop i in farm, and income source i in household. The Shannon diversification index considers the relative income abundance among crop and income sources while the Simpson index reflects the degree to which one or several farm products and income

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§ Detail explanation of climate variables are in 2.3.3

sources dominate per household (Bozzola and Smale, 2020). When Shannon diversification index is zero, it also captures households who do not diversify their farm products and income sources.

2. Household food security indicators

To measure household food security, we use HDDS (Kennedy et al., 2011) and per capita food expenditure. HDDS is calculated by summing the number of 12 food groups per household over 7-days recall period (Keding et al., 2012). 12 food groups include ‘cereals’, ‘white tuber and roots’, ‘vegetables’, ‘fruits’, ‘meat’, ‘eggs’, ‘fish and other seafood’, ‘legumes, nuts, and seeds’, ‘milk and milk products’, and ‘oils and fats’, ‘sweets’, and ‘spices, condiments and beverages’ (Kennedy et al., 2007). In addition, per capita food expenditure is deflated to BIHS 2011/2012. The two indicators measure different dimensions of food security. HDDS measures the food utilization dimension and intake of micronutrient (Mulwa and Visser, 2020; Kennedy et al., 2007) while per capita food expenditure measures the food access dimension of food security since it captures other sources of food besides own production (Mulwa and Visser, 2020).

3.Climate indicators

Climate indicators are measured by 64 district-level rainfall (mm) and temperature (°C). District-level rainfall and temperature are divided into seasonal weather, based on four season defined by Bangladesh Meteorology Department (2013). We use historical weather information to account for the climate normal of the division, measured by the 20-year information before the survey period. For example, we take averages for each seasonal temperature and rainfall variable over 1992–2011/12 for the year 2011/12, 1995–2015 for the year 2015, 1998–2018/19 for the year 2018. Using 20-year average rainfall and average temperature, we create rainfall shock variables and temperature shock variables. Rainfall shock captures the contemporaneous rainfall shock, calculated as logarithm seasonal rainfall – logarithm 20-year seasonal rainfall. Temperature shock captures the contemporaneous temperature shock, calculated as logarithm seasonal temperature – logarithm 20-year temperature shock.

Table 1: Climate of Bangladesh

Seasons	Period	Weather Events
Summer (Pre-monsoon)	March to May	Cyclone, Heat Wave
Rainy Season (Southwest Monsoon)	June to September	Heavy rain, Monsoon Depression, Flood
Autumn (Post-monsoon)	October to November	Cyclone, Tornado
Winter (Northeast Monsoon)	December to February	Drought, Cold Wave

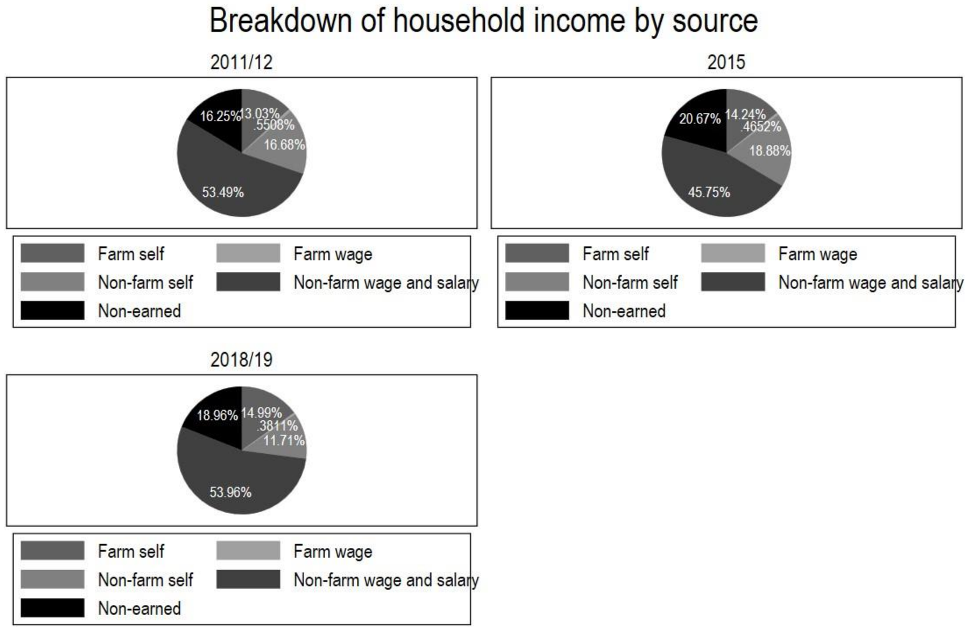
Source: Bangladesh Meteorology Department (2013)

Table 2 Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Obs	Mean	Std. Dev.	Obs	Mean	Std. Dev.
		2011/12			2015			2018/19	
Household Dietary Diversity Score	6,503	9.121329	1.423172	6,436	9.766781	1.23978	5,604	9.939507	1.18369
Per capita food expenditure (deflated to baseline value)	6,503	1598.295	864.4254	6,435	1713.36	1018.853	5,604	1717.148	915.8216
Crop Diversification Index	3,409	0.4487782	0.255563	3,384	0.4263972	0.263477	2,937	0.398773	0.262216
Income diversification index	6,427	0.3115912	0.220948	6,356	0.3068185	0.2214402	5,587	0.301938	0.222593
share of households adopting crop diversification within the union	3,409	0.4846525	0.2014	3,384	0.4310233	0.212506	2,937	0.223891	0.000046
share of households adopting income diversification within the union	6,427	0.7905039	0.132135	6,356	0.7668145	0.1286159	5,587	0.504539	3.52E-05
20-year summer average rainfall (mm)	6,503	439.0042	188.275	6,436	432.4396	189.6589	5,604	491.0543	225.4902
20-year rainy season average rainfall (mm)	6,503	1532.518	480.0489	6,436	1523.923	501.0747	5,604	1541.596	542.2929
20-year autumn average rainfall (mm)	6,503	198.6463	40.35466	6,436	201.5855	41.17153	5,604	197.0214	41.65689
20-year winter average rainfall (mm)	6,503	472.6912	190.1535	6,436	462.492	190.08	5,604	523.4257	229.762
Summer rainfall(mm)	6,503	406.3399	134.8079	6,436	290.7769	126.1155	5,604	612.6117	241.3939
Rainy season rainfall(mm)	6,503	1628.678	594.5336	6,436	1462.629	514.2468	5,604	1222.214	619.6065
Autumn rainfall(mm)	6,503	40.29002	38.62283	6,436	63.48036	33.03141	5,604	106.4123	90.43806
Winter rainfall(mm)	6,503	24.153	15.67674	6,436	39.22923	25.96695	5,604	77.29334	32.99433
20-year summer rainfall (SD)	6,503	121.8993	42.67297	6,436	128.3017	43.35819	5,604	140.7506	49.09811
20-year rainy season rainfall (SD)	6,503	165.3239	57.70312	6,436	161.7289	60.91518	5,604	168.9498	67.2956
20-year autumn rainfall (SD)	6,503	119.2247	19.97377	6,436	120.6526	20.38923	5,604	121.9801	18.66285
20-year winter rainfall (SD)	6,503	110.5803	42.48591	6,436	113.7773	42.95136	5,604	126.6744	49.44652
20-year summer average temperature(C)	6,503	27.68068	0.883578	6,436	27.79148	0.8827921	5,604	27.64167	0.897232

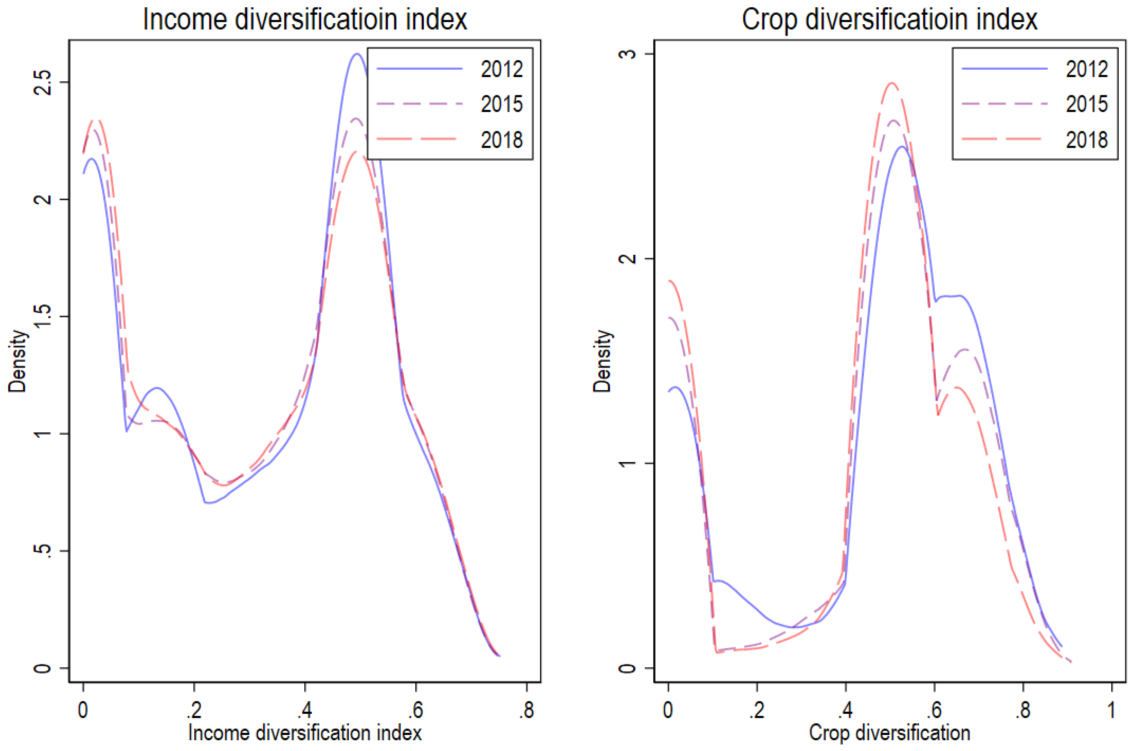
20-year rainy season average temperature(C)	6,503	28.97243	0.410056	6,436	29.08218	0.4144444	5,604	29.15501	0.417321
20-year autumn average temperature(C)	6,503	26.01287	0.471038	6,436	25.99281	0.4741956	5,604	25.93619	0.477286
20-year winter average temperature(C)	6,503	23.86605	0.687203	6,436	23.92257	0.6868437	5,604	23.88129	0.717959
20-year summer temperature (SD)	6,503	1.685884	0.194974	6,436	1.682956	0.2124023	5,604	1.587402	0.189411
20-year rainy season temperature (SD)	6,503	0.5174502	0.052175	6,436	0.5282727	0.0545761	5,604	0.512715	0.053733
20-year autumn temperature (SD)	6,503	1.832646	0.130981	6,436	1.864478	0.1510002	5,604	1.89053	0.163174
20-year winter temperature (SD)	6,503	4.174167	0.45369	6,436	4.22685	0.4782732	5,604	4.113024	0.4824
Summer average temperature(C)	6,503	27.44447	0.717942	6,436	28.4107	0.9525178	5,604	27.19076	0.863769
Rainy season average temperature(C)	6,503	29.10577	0.371709	6,436	29.4076	0.3957363	5,604	29.64823	0.456709
Autumn season average temperature(C)	6,503	26.14575	0.529558	6,436	25.97345	0.5570937	5,604	25.47971	0.627163
Winter average temperature(C)	6,503	19.79986	0.853973	6,436	20.19248	0.8315714	5,604	20.23077	0.805967
Male(=1)	6,503	0.8225434	0.382084	6,435	0.8114996	0.3911416	5,604	0.789258	0.407872
Age of HH	6,503	44.17131	13.98042	6,435	45.76317	13.83745	5,604	46.58672	13.79042
Household size	6,503	4.195756	1.628048	6,435	4.957576	1.997722	5,604	5.76838	2.399259
Schooling year of HH	6,502	3.330206	3.937874	6,433	3.52153	3.95417	5,601	3.714158	4.016648
Livestock ownership(=1)	5,330	0.927955	0.258587	6,435	0.157265	0.3640787	5,603	0.208103	0.405987
Farm Size(decimal)	6,503	91.31112	145.4239	6,435	97.57578	155.5219	5,604	88.32784	131.3279
Market access (minute)	6,411	17.44642	10.72423	6,344	15.77427	9.58093	5,580	13.28136	8.513712
Road access (minute)	6,355	14.65539	11.49075	6,217	12.16358	10.96112	5,535	12.11491	11.4361
Access to agricultural extension service (=1 if yes)	6,503	0.060895	0.239156	3,462	0.1288273	0.3350571	3,974	0.170861	0.376435
Irrigation(=1)	3,409	0.8647697	0.34202	6,435	0.4418026	0.4966401	5,604	0.440757	0.496522

Source: Bangladesh Integrated Household Survey 2011/12, 2015, 2018/19, 100 decimals is 0.4 ha, currency is Bangladesh taka



Source:
BIHS2011/12, 2015, and 2018/19 calculated by author

Figure 2: Breakdown of household income by source



Source:
BIHS2011/12, 2015, and 2018/19 calculated by author

Source:
BIHS2011/12, 2015, and 2018/19 calculated by author

Figure 3: Density distribution of diversification index

Empirical framework

As stated in the introduction, this paper investigates: (1) how farmers respond to climate variability through livelihood diversification; (2) impact of livelihood diversification on household food security; and (3) heterogeneous impacts of livelihood diversification on household food security across the per capita food expenditure. There are some challenges in estimating the models for livelihood diversification and household food security, particularly regarding how the unobserved heterogeneity and potential endogeneity of livelihood diversification variables are addressed. Below we discuss the estimated models and how these issues are addressed in this paper.

We employ the fixed effect Poisson/OLS regression with a control function to deal with endogeneity based on both two-stage residual inclusion (2SRI) developed by Terza et al. (2008) and two-stage least squares (2SLS) approach for controlling endogeneity because HDDS, which is an outcome variable, is a count variable and Wooldridge (2010) suggests the use of the 2SRI method for count data models. Another outcome variable is per capita food expenditure and the outcome equation for per capita food expenditure is estimated by 2SLS. Controlling endogeneity involves using the residuals from the first stage regression of the endogenous variable to control for and test endogeneity in the structural equation (see 3.5). Therefore, we use 2SRI and 2SLS to investigate the impact of livelihood diversification on household food security in this study. Based on our conceptual framework, the econometric models are specified as below:

$$\mathrm{D_{it}} = \beta_0 + \beta_1 \mathrm{C_{dt}} + \beta_2 \mathrm{z_{it}} + \beta_i \mathrm{X_{it}} + \mathrm{a_i} + \rho_t + \epsilon_{it1} \tag{4}$$

where $\mathrm{D_{it}}$ is a variable of the diversification strategy of taken by household i at time t, $\mathrm{C_{it}}$ is a climate variable which is adjusted to district levels d, $\mathrm{z_{it}}$ is an instrument measured by the share of households in a union, which is the smallest administrative level in Bangladesh, (excluding the household considered) adopting the considered diversification strategy (whose diversification index is greater than zero), which we call it a peer effect variable. $\mathrm{X_{it}}$ is a control variable. In Equation 4, $\mathrm{a_i}$ is the individual fixed effect to control for unobservable time-invariant heterogeneity among farmers, which may be due to differences in skills, access to information, and risk aversion (Maggio et al., 2021; Islam et al., 2018), ρ_{it} is a time dummy accounting for time trends, and ϵ_{it} is an error term. The first stage regression is estimated by fixed effect OLS.

$$\log(\mathrm{y_{it}}) = \alpha_0 + \alpha_1 \mathrm{D_{it}} + \alpha_2 \mathrm{C_{dt}} + \alpha_i \mathrm{X_{it}} + \alpha_i \mathrm{r_{it}} + \mathrm{a_i} + \rho_t + \epsilon_{it2} \tag{5}$$

where, $\mathrm{y_{it}}$ is an outcome variable which presents HDDS and per capita food expenditure, $\mathrm{r_{it}}$ is the residual from the Equation 4, and ϵ_{it2} is an error term. In terms of the relationship between livelihood diversification and HDDS, using Poisson regression is a natural starting point because our dependent variable HDDS is a count variable (Islam et al., 2018; Kouser and Qaim, 2011). Moreover, to investigate the relationship between livelihood diversification and per capita food expenditure, we use standard individual fixed effect model. Regarding the residuals, the null hypothesis is that the coefficients are zero in the regression-based Hausman test for the exogeneity of livelihood diversification variables. The significant coefficients of the residuals term in the equation (5) indicate the presence of endogeneity and possible reduced bias compared with the estimation of without IV approaches.

Identification strategy

1.Controlling for unobserved heterogeneity

Livelihood diversification decision is self-selection thus, there is a possible endogeneity. In estimating panel models, an important issue is how to handle the time-invariant unobserved individual effect a_i. which would affect individual livelihood diversification decision. An advantage of a fixed effects is that unobserved characteristics of a household that do not change over time and might affect its dietary behavior do not bias results (Mehraban and Ickowitz, 2021). Thus, we estimated Fixed Effects model to deal with time-invariant unobserved heterogeneity which would cause endogeneity of livelihood diversification.

2. Controlling for endogenous regressor

Although we employ the fixed-effect model, the model might produce biased estimates for the coefficients of diversification strategies due to unsolved endogeneity issues (Maggio et al., 2021). The main variable of interest, maize adoption, is itself a decision variable, improved and, hence, may be correlated with the error term in the outcome equations. There are three possible endogenous problems. First, there would be reverse causality. Our hypothesis is that diversification strategies improve HDDS. However, a household may adopt a coping strategy because their consumption level drops (Gao and Mills, 2018). Second, there would be self-selection bias. Farmers can decide diversification strategies on their own and unobserved factors would affect their decision making. In this case, systematic differences among farmers might affect their decision, such as socioeconomic and demographic factors (Islam et al., 2018). Third, there would be omitted variable bias caused by time-varying and unobservable variables, as Maggio et al. (2021) stated. 2SRI can deal with those possible endogenous problems, whatever the specification model is a linear or nonlinear function (Terza et al., 2008).

To perform 2SRI and 2SLS, we need valid instruments which affect the endogenous explanatory variables which are farm and income diversification, but do not affect household food security (exclusive restriction in Angrist et al. (1996)). Based on economic literature on the important role of peer effect in the decision to adopt an agricultural practice (Conley and Christopher, 2001; Munshi, 2004), the instruments measure the share of household diversifying livelihood within a union. The variable is calculated by the percentage of households in the union (excluding the household considered) adopting the considered diversification strategy (whose diversification index is greater than zero) (Asfaw et al., 2019; Maggio et al., 2021). In past studies such as Birthal et al. (2015), Arslan et al. (2017), Asfaw et al. (2019), and Maggio et al. (2021), similar peer effect variables are employed as instruments in studying climate change adaptation and household livelihood outcome. The logic behind is this that the neighbor's decisions would affect households' decision of adaptation strategies but not directly affect household food security. As a statistical test, we report the diagnostic test for weak instruments based on the Cragg–Donald Wald F-test (Staiger and Stock, 1997).

Results and discussion

Determinants of diversification strategies

Table 3 shows determinants of livelihood diversification. As for the peer effect which is the instrumental variable, the findings show that households located in a union characterized by a higher percentage of farmers adopting a specific diversification strategy exhibit higher levels of diversification. The result is consistent with past studies by Birthal et al. (2015), Arslan et al. (2017), Asfaw et al. (2019), and Maggio et al. (2021). Moreover, the null hypothesis about the weakness of the instruments is rejected because F-statistic is significant in the estimations of both crop and income diversification [5].

Climate variability are supposed to act as a push factor for farm diversification (Asfaw et al., 2019). Positive rainfall shock in winter increase crop diversification, while negative rainfall shock in winter increases income diversification. It indicates that more rainfall compared to historical rainfall in winter increase crop diversification and less rainfall compared to historical rainfall in winter increase income diversification. Moreover, larger 20-year autumn temperature SD increase crop diversification, indicating that the higher riskiness of temperature in autumn increase crop diversification as a coping strategy. As such, climate variability in the past could drive households to hedge against future climate variability through livelihood diversification. They are consistent with past studies (Asfaw et al., 2018, 2019; Salazar-Espinoza et al., 2015; Arslan et al., 2017; Asravor, 2018; PiedraBonilla et al. (2020)).

In terms of socioeconomic variables, the relationship between gender of household head and livelihood diversification is unclear from past studies. Our results also show that the gender of household head is significant for crop diversification and income diversification. However, age of household head is significant for crop diversification but not income diversification. Greater farmland size is found to be a positively significant determinant for both diversification strategies. The results are consistent with Asfaw et al. (2018, 2019). On the other hand, the relationship between education level of household head and diversification is insignificant. A

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[5] We reject the null hypothesis of weak instruments based on the Cragg–Donald Wald F statistic (18.475 for crop diversification and 2 1.405 for income diversification), which is used as a rule of thumb to test the hypothesis (Staiger and Stock, 1994; Isaiah et al., 2018)

plausible explanation offered by Asfaw et al. (2019) is that wealthier and more educated households have more opportunities for off-farm labor and crop diversification but they could be less risk averse. Thus, the empirical relationships are mixed and unclear.

As for agronomic, institutional and infrastructure variables, the endowment of farm land is significantly related with crop and income diversification. Owning more land enhance the opportunity to diversify the crop and income portfolio. This result is consistent with Asfaw et al. (2018), and Amfo and Ali (2020). Moreover, usage of irrigation and access to agricultural extension service are significant. It indicates that income from non-farm sources in the form of liquid cash may be important for the timely purchase of farm inputs such as irrigation pumps, or through the ability to hire wage labor, leading to improved cultivation practices and higher farm productivity (Martin and Lorenzen, 2016). Also, consistent with Asfaw et al. (2019), farm households obtain information about new agricultural product and adaptive strategies through agricultural extension service so that they can consider diversifying their farm products and income source.

Table 3: Determinants of diversification strategies (OLS FE, 1st stage)

	(1) Crop diversification	(2) Income diversification
Share of households adopting crop diversification within the union	0.093***	
	(0.022)	
Share of households adopting income diversification within the union		0.137***
		(0.031)
Rainfall shock in summer	-0.004	-0.006
	(0.017)	(0.015)
Rainfall shock in rainy season	0.001	0.004
	(0.028)	(0.025)
Rainfall shock in autumn	0.002	0.007**
	(0.004)	(0.004)
Rainfall shock in winter	0.009*	-0.017***
	(0.006)	(0.005)
20-year summer rainfall SD(log)	0.358	0.026
	(0.344)	(0.289)
20-year rainy season rainfall SD(log)	0.054	0.112
	(0.086)	(0.074)
20-year autumn rainfall SD(log)	-0.483***	0.085
	(0.108)	(0.096)
20-year winter rainfall SD(log)	-0.420	-0.129
	(0.430)	(0.364)
Temperature shock in summer	0.961	0.443
	(0.662)	(0.596)
Temperature shock in rainy season	1.285	0.423
	(0.924)	(0.816)
Temperature shock in autumn	-0.178	0.135
	(0.330)	(0.294)
Temperature shock in winter	0.063	0.319
	(0.336)	(0.287)
20-year summer temperature SD(log)	0.055	-0.870***
	(0.351)	(0.312)
20-year rainy season temperature SD(log)	-0.244**	0.091
	(0.112)	(0.105)
20-year autumn temperature SD(log)	0.812**	-0.148
	(0.318)	(0.306)
20-year winter temperature SD(log)	-2.060***	1.268**
	(0.688)	(0.580)
Male(=1, if yes)	0.032*	0.029*
	(0.018)	(0.016)
Age of HH	0.001**	0.001
	(0.001)	(0.001)
Household size	0.003	-0.002
	(0.004)	(0.003)

Schooling year of HH	-0.003	0.000
	(0.003)	(0.002)
Farm size (log)	0.053***	0.034***
	(0.007)	(0.006)
Livestock ownership(=1, if yes)	0.008	0.009
	(0.007)	(0.006)
Irrigation(=1, if yes)	0.150***	0.034***
	(0.013)	(0.010)
Market access (minute)	0.000	-0.000
	(0.000)	(0.000)
Road access (minute)	-0.000	-0.000
	(0.000)	(0.000)
Access to agricultural extension service (=1, if yes)	0.021***	0.023***
	(0.007)	(0.007)
Individual FE	Yes	Yes
Year FE	Yes	Yes
Observations	7487	8034

Robust standard errors in parentheses
* p<0.1, ** p<0.05, *** p<0.01

Impact of livelihood diversification on household food security

In this section, we present the impact of the two diversification strategies on household food security. Table 4 presents the result of Equation 5 by estimating the exponential mean model by Poisson fixed effect and linear model by OLS fixed effect. First, column (1) and (2) show that the impact of crop diversification on household food security. We found that crop diversification does not have significant impact on HDDS and per capita food expenditure, in contrast to past studies by Islam et al. (2018); Amfo et al. (2021). Second, column (3) and (4) present the impact of income diversification on household food security. Income diversification significantly increases per capita food expenditure but not HDDS. It indicates that 0.1 increase in income diversification leads to 12.34% increase in per capita food expenditure. The results are consistent with past research by Jones (2017); Asfaw et al. (2018, 2019); Mulwa and Visser (2020); Dedehouanou and McPeak (2020), and, Amfo et al. (2021). Income diversification improves not only food availability, therefore resilience capacities, also would reduce poverty through off-farm employment (Davis et al.,2010: Khandker,2012). Although Asfaw et al. (2019) and Islam et al. (2018) showed livelihood diversification improve HDDS, our results show that livelihood diversification does not improve HDDS. The plausible explanation is that crop and income diversification do not mitigate the impact of climate shock but Asfaw et al. (2019) and Islam et al (2018) did not control climate variability in their models. However, our results still indicate that income diversification improves household food security which makes households resilience toward poverty and famine under climate change in Bangladesh.

Although our research question was to assess the impact of livelihood diversification on household food security, we report other significant variables explaining household food security in our model. First, dry shock in summer decrease per capita food expenditure while larger 20-year summer rainfall SD decrease HDDS. These results indicate that rainfall variability affect household food security. On the other hand, heat wave in rainy season decreases HDDS while cold wave in summer decreases HDDS. In addition, larger 20-year autumn temperature SD decreases HDDS and per capita food expenditure. Overall, our results show that greater climate variability affects household food security. Our findings are in line with Porter (2012) who found lower rainfall relative to local norms can cause significant reductions in consumption, Tibesigwa et al. (2015) found climate change will food adequacy for households who mainly participate in subsistence agriculture, and Alem and Colmer (2021) who found that greater rainfall variability is associated with significant reductions in real per capita consumption.

Regarding other control variables, Household size is significantly associated with HDDS and per capita food expenditure. This relationship is reasonable because larger-size families consume more food within a household, resulting in more various food groups and less per capita food expenditure due to budget constraint. This result is consistent with past research by Islam et al. (2018). Consistent with Jones (2017), Islam et al. (2018), and Asfaw et al. (2019), larger farm size and better market access are significant to per capita food expenditure. It indicates that natural capital and infrastructure increase household food security.

Table 4: Impact of livelihood diversification on household food security (Poisson /OLS FE with IV, 2nd stage)

	(1) HDDS	(2) Per capita food expenditure (log)	(3) HDDS	(4) Per capita food expenditure (log)
Crop Diversification Index	0.122	0.459		
	(0.139)	(0.376)		
Income diversification index			0.014	1.234**
			(0.009)	(0.490)
Rainfall shock in summer	0.006	0.004	0.000	0.080**
	(0.009)	(0.026)	(0.009)	(0.035)
Rainfall shock in rainy season	0.018	-0.062	0.014	0.037
	(0.016)	(0.044)	(0.015)	(0.057)
Rainfall shock in autumn	0.001	0.010	0.001	-0.002
	(0.002)	(0.006)	(0.002)	(0.009)
Rainfall shock in winter	-0.003	-0.015	-0.001	0.007
	(0.004)	(0.010)	(0.004)	(0.015)
20-year summer rainfall SD(log)	-0.398*	-0.503	-0.302*	-0.971
	(0.209)	(0.560)	(0.183)	(0.665)
20-year rainy season rainfall SD(log)	0.123**	-0.056	0.126***	0.004
	(0.048)	(0.135)	(0.049)	(0.179)
20-year autumn rainfall SD(log)	0.050	0.345	0.017	-0.079
	(0.092)	(0.246)	(0.060)	(0.222)
20-year winter rainfall SD(log)	0.379	0.271	0.266	0.633
	(0.259)	(0.703)	(0.232)	(0.852)
Temperature shock in summer	-0.254	3.428***	-0.112	1.664
	(0.409)	(1.169)	(0.368)	(1.420)
Temperature shock in rainy season	-0.299	-4.942***	-0.258	-2.287
	(0.541)	(1.507)	(0.499)	(1.879)
Temperature shock in autumn	-0.320	1.241**	-0.393**	1.212*
	(0.195)	(0.544)	(0.181)	(0.695)
Temperature shock in winter	0.096	-0.587	0.095	-1.669**
	(0.184)	(0.520)	(0.183)	(0.688)
20-year summer temperature SD(log)	0.089	0.107	0.175	-0.357
	(0.197)	(0.545)	(0.203)	(0.771)
20-year rainy season temperature SD(log)	0.078	0.486**	0.025	0.165
	(0.079)	(0.210)	(0.065)	(0.241)
20-year autumn temperature SD(log)	-0.456**	-3.349***	-0.356*	-1.660**
	(0.223)	(0.593)	(0.194)	(0.701)
20-year winter temperature SD(log)	0.424	-0.124	-0.056	0.691
	(0.549)	(1.449)	(0.404)	(1.467)

Male(=1, if yes)	0.021*	-0.064**	0.021**	-0.032
	(0.011)	(0.029)	(0.010)	(0.034)
Age of HH	-0.000	0.000	-0.000	0.000
	(0.000)	(0.001)	(0.000)	(0.001)
Household size	0.005**	-0.103***	0.005***	-0.084***
	(0.002)	(0.006)	(0.002)	(0.007)
Schooling year of HH	-0.000	-0.000	0.000	0.001
	(0.002)	(0.004)	(0.001)	(0.005)
Livestock ownership(=1, if yes)	0.002	0.008	0.000	0.014
	(0.004)	(0.012)	(0.004)	(0.015)
Farm size (log)	0.002	0.043*	0.006	-0.009
	(0.009)	(0.023)	(0.006)	(0.021)
Market access (minute)	-0.000	-0.001**	-0.000	-0.001
	(0.000)	(0.001)	(0.000)	(0.001)
Road access (minute)	-0.000	-0.000	-0.000	-0.001
	(0.000)	(0.000)	(0.000)	(0.001)
Access to agricultural extension service (=1, if yes)	-0.001	0.020	-0.000	-0.015
	(0.005)	(0.015)	(0.005)	(0.020)
Irrigation(=1, if yes)	-0.022	-0.078	-0.005	-0.049*
	(0.022)	(0.059)	(0.007)	(0.026)
Residual-income			0.034	
			(0.131)	
Residual-crop	-0.119			
	(0.139)			
Individual FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	7487	7487	8034	8033

Robust standard errors in parentheses
Instrumental variables (% of households adopting a considered diversification strategy within a union)
* p<0.1, ** p<0.05, *** p<0.01

Heterogeneous impact of livelihood diversification on household food security

In this section, we entangle the heterogeneous relationship among the effect of livelihood diversification on a distribution of per capita food expenditure. Using the Quantile IV fixed effect regression, we address the distributional effect of livelihood diversification on per capita food expenditure conditioned on 25%, 50%, and 75% quantile. Because per capita food expenditure is continuous while HDDS is a count variable, we focus on the distributional effect on the per capita food expenditure. As Barrett et al. (2001b) argue that the empirical regularity of a positive association between income diversification and wealth, consumption or earnings leads too many studies to the facile conclusion that promoting diversification is equivalent to assisting the poor. Following Asfaw et al. (2019), to identify policy options that are better tailored to the needs of a socioeconomically diverse rural population, we investigate the heterogeneous impact of livelihood diversification on per capita food expenditure. Some studies show the heterogeneous effect of livelihood diversification (Reardon et al., 2000), the heterogeneous impact of crop and income between high- and low-income households (Asfaw et al., 2018, 2019). Moreover, Tambet and Stopnitzky (2021) showed that individual and household characteristics affect the heterogeneity of farmer responses to shocks and Dagunga et al. (2020) showed that the impact of crop diversification reduces multidimensional poverty at the lower and middle quantiles of diversification while income diversification was found to reduce multidimensional poverty at the higher levels of diversification. To the best of our knowledge, few studies have investigated the heterogeneous impact of livelihood diversification on household food security across the distribution of per capita food expenditure at the context of South Asia. As Barrett et al. (2001b) found, diversification can rise through increased off-farm, unskilled labor that does little to reduce household risk exposure or increase expected income. Therefore, we hypothesize that livelihood diversification are more effective to households who spend more food consumption than household who are relatively poor

Table 5 reports the estimated coefficients associated with the two diversification indices at three points of the per-capita food expenditure distribution (quantile 0.25, 0.50, 0.75)[6]. In terms of crop diversification, all the coefficients are insignificant. On the other hand, at column (4) and (5), the impact of income diversification is positively significant while it is insignificant at column (6). Moreover, the impact of a marginal increase in income diversification is higher at the lower and middle segments of the distribution. Thus, the impact of diversification strategies is generally higher for the poorer. The result indicates that income diversification works for the poorer more effectively, which is consistent with Asfaw et al. (2018, 2019).

The findings draw two lessons from the results. First, even when we investigate the heterogeneous impact of crop diversification, all the coefficients are insignificant at all quantiles. Second, the impact of income diversification tends to decline moving toward the top of the food expenditure distribution. Asfaw et al. (2019) explain that this is probably due to the fact that the richest farmers have other available instruments to cope with production risk (in particular the risk related to climate shocks such as extreme weather events), while for the poorest, diversification is often the only viable alternative. These findings highlight the importance of developing policies and programs that are designed not only just to promote the livelihood diversification as adaptive strategies and mitigating risks but also to strengthen the support for poorer and vulnerable households to adapt to climate change.

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[6] Full regression results are in Appendix A.

Table 5: Quantile effect of livelihood diversification on per capita food consumption expenditure

	(1) 25% quantile	(2) 50% quantile	(3) 75% quantile	(4) 25% quantile	(5) 50% quantile	(6) 75% quantile
Crop diversification	0.870	1.075	0.545			
	(0.705)	(0.681)	(0.826)			
Income diversification				2.012***	1.964**	0.649
				(0.759)	(0.774)	(0.989)
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7486	7486	7486	8033	8033	8033

Robust standard errors in parentheses

Instrumental variables (% of households adopting a considered diversification strategy within a union)

* p<0.1, ** p<0.05, *** p<0.01

Robustness checks

The causal effect of crop/income diversification on livelihood may vary with the way the diversification index is measured. Therefore, we use alternative indicators of livelihood diversification, which is Shannon diversification index considering evenness of crop and income to test the robustness our main indicator of livelihood diversification in this section.

Table 6 shows the determinants of livelihood diversification[7]. Same as the results in Table

3, the higher the percentage of population in a union implementing livelihood diversification,

the higher the probability that the household diversifies either in crop production or income source. Moreover, Table 7 shows the impact of livelihood diversification on household food security with the alternative measurement. Only the impact of income diversification on per capita food expenditure is positively significant, same as Table 4. In addition, Table 8 shows the quantile effect of livelihood diversification on per capita food expenditure. In terms of income diversification, 25% and 50% quantiles are positively significant and the lower and middle quantile has the impact on household food security, same as Table 5. Results in Table 7

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[7] A full regression table is in Appendix A

and 8 suggest that our finding income diversification mainly benefits more to the poorer than richer are robust.

Table 6: Robustness of the results with alternative measure of livelihood diversification (OLS FE)

	(1) Crop diversification (Shannon)		(2) Income diversification (Shannon)	
Share of households adopting crop diversification within the union	0.189***	(0.040)		
Share of households adopting income diversification within the union			0.280***	(0.048)
Individual FE	Yes		Yes	
Year FE	Yes		Yes	
Control Variables	Yes		Yes	
Observations	7487		8076	

Standard errors in parentheses
*P<0.1, ** p<0.05, *** p<0.01

Table 7: Robustness of the results with alternative measure of livelihood diversification (Poisson /OLS FE with IV)

	(1) HDDS	(2) Per capita food expenditure (log)	(3) HDDS	(4) Per capita food expenditure (log)
Crop diversification (Shannon)	0.060	0.226		
	(0.068)	(0.183)		
Income diversification (Shannon)			0.028	0.620***
			(0.063)	(0.227)
Individual FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Control Variables	Yes	Yes	Yes	Yes
Number of households	7487	7487	8076	8075

Robust standard errors in parentheses
Instrumental variables (% of households adopting a considered diversification strategy within a union)
*p<0.1, ** p<0.05, *** p<0.01

Table 8: Quantile effect of livelihood diversification on per capita food expenditure with an alternative measurement (IV FE)

	(1) 25% quantile	(2) 50% quantile	(3) 75% quantile	(4) 25% quantile	(5) 50% quantile	(6) 75% quantile
Crop diversification (Shannon)	1.151	1.649*	0.968			
	(0.951)	(0.916)	(1.108)			
Income diversification (Shannon)				0.952***	0.970***	0.238
				(0.351)	(0.359)	(0.459)
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7486	7486	7486	8075	8075	8075

Robust standard errors in parentheses
Instrumental variables (% of households adopting a considered diversification strategy within a union)
* p<0.1, ** p<0.05, *** p<0.01

Conclusions and policy implications

The study contributes to a slim body of literature examining determinants of diversification strategies including both farm and income diversification, in the context of Bangladesh and South Asia. Moreover, impact of livelihood diversification on household food security is examined by using three wave nationally representative panel rural household survey carried out in 2011/12, 2015, and 2018/19, which is combined with geo-referenced historical rainfall and temperature data. Furthermore, our empirical analysis considers the endogeneity of livelihood diversification on household food security.

In line with past studies, the results show that the proximity to neighbor households adopting diversification increases farm and income diversification. Moreover, we find that climate variability, farm size, irrigation usage, and access to agricultural extension service are drivers of livelihood diversification. As for the average impacts of livelihood diversification, this study finds that income diversification is enhancing per capita food expenditure. Moreover, results show that the impact of income diversification is higher for the lower and middle quantile of per capita food expenditure distribution. This is probably due to the fact that income diversification through off-farm income is the major instruments improving food insecurity for the poorer and vulnerable households compared to the richer households who can afford to adopt more adaptation strategies

Some caveats related to the inherent nature of the key variables deserve further comments. The dataset includes not only farm households but also non-farm households in rural Bangladesh, so around half of the household data is not used and it occurs the possibility of non-representativeness of the sample. Moreover, crop diversification index includes only the land share of each crop. Due to the data availability, we are not able to consider fish and poultry diversity in the index. Further data collection is needed to overcome these caveats.

Regardless of these caveats, results from the study offer important policy-relevant insights of improving household food security. Our findings corroborate Barrett et al. (2001a), Barrett et al. (2001b), and Olale and Henson (2013), that income diversification increases per capita food expenditure. Therefore, income diversification should be promoted and considered as a possible strategy for reversing the food insecurity through more opportunities of off-farm income, social safety-net programs such as pension or insurance. Moreover, our results also show the heterogeneous impact of income diversification across the food expenditure distribution, which indicate that the poorer household enjoy more benefits of income diversification.

Consequently, designing policies to promote diversification strategies is crucial to target the poor farmers who have difficulties in terms of infrastructure, and institutional environment. A policy variable identified in the study as a key determinant to diversification decisions is that of access to irrigation related to both farm and income diversification. Access to irrigation should be therefore targeted towards enhancing opportunities of farm resilience for sustainable production, to mitigate against weather variability and climatic shocks like droughts. Improving access to irrigation will also ensure many farm households can afford to do non-farm activities because they spend less time for farm management.

Our findings also suggest that more extension contacts should be considered when designing programs to effectively assist farmers in coping with climate change. More access to agricultural extension service would enable farmers to have access to information of both farm and income diversification, and practices that constitute climate smart agriculture, for sustainable production. Moreover, building infrastructure should be also effective for household food security because our findings show better market access increase per capita food expenditure and Barrett et al. (2001b) mention that increased investment in the physical capita, institutional access, and infrastructure necessary to make markets accessible for the rural poor.

There is a consensus that climate change impacts will continue to be felt in the next few decades, despite the global efforts to mitigate emissions that cause the global warming problem (Mulwa and Visser, 2020). Since non-farm income is dominant in rural household income and income diversification improve household food security, policy makers in South Asia thus need to urgently consider ways to fast-track access to non-farm opportunities in the rural areas of South Asia, for resilient livelihoods in the face of these challenges.

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A Appendix tables

Table A1: Quantile effect of livelihood diversification (OLS FE with IV)

	(1) 25% quantile	(2) 50% quantile	(3) 75% quantile	(4) 25% quantile	(5) 50% quantile	(6) 75% quantile
Crop diversification	0.870	1.075	0.545			
	(0.705)	(0.681)	(0.826)			
Income diversification				2.012***	1.964**	0.649
				(0.759)	(0.774)	(0.989)
Rainfall shock in summer	0.006	0.002	0.095	0.052	0.072	0.121*
	(0.054)	(0.052)	(0.062)	(0.057)	(0.054)	(0.065)
Rainfall shock in rainy season	0.076	0.077	-0.027	0.097	0.137	-0.010
	(0.093)	(0.087)	(0.108)	(0.090)	(0.085)	(0.105)
Rainfall shock in autumn	0.023*	0.006	-0.002	0.005	-0.008	-0.009
	(0.013)	(0.013)	(0.015)	(0.014)	(0.014)	(0.017)
Rainfall shock in winter	-0.028	-0.020	-0.004	0.013	0.017	0.013
	(0.018)	(0.018)	(0.022)	(0.022)	(0.022)	(0.026)
20-year summer rainfall SD(log)	-0.734	-0.797	-0.248	-1.336	-1.735*	-0.935
	(1.081)	(1.034)	(1.225)	(1.092)	(1.029)	(1.246)
20-year rainy season rainfall SD(log)	0.240	0.204	-0.105	0.154	-0.028	-0.089
	(0.283)	(0.279)	(0.333)	(0.281)	(0.282)	(0.343)
20-year autumn rainfall SD(log)	0.788*	0.716	-0.133	0.226	0.050	-0.406
	(0.451)	(0.437)	(0.548)	(0.329)	(0.336)	(0.437)
20-year winter rainfall SD(log)	0.271	0.164	-0.682	1.278	1.496	0.194
	(1.377)	(1.299)	(1.522)	(1.410)	(1.308)	(1.581)
Temperature shock in summer	-1.793	1.122	4.305	-1.083	1.070	3.611
	(2.362)	(2.301)	(2.895)	(2.202)	(2.175)	(2.759)

Temperature shock in rainy season	-2.007	-1.800	-3.178	-2.516	0.424	-1.773
	(3.155)	(3.012)	(3.687)	(2.915)	(2.786)	(3.400)
Temperature shock in autumn	1.165	1.097	3.245**	0.419	-0.055	1.835
	(1.176)	(1.123)	(1.330)	(1.103)	(1.095)	(1.288)
Temperature shock in winter	-1.137	-0.996	-2.455**	-1.458	-1.200	-2.128*
	(1.144)	(1.044)	(1.224)	(1.099)	(1.019)	(1.227)
20-year summer temperature SD(log)	0.561	-0.451	-1.415	0.993	-0.612	-2.203*
	(0.987)	(0.960)	(1.127)	(1.125)	(1.102)	(1.332)
20-year rainy season temperature SD(log)	0.812**	0.217	-0.039	0.580	-0.000	-0.100
	(0.394)	(0.370)	(0.425)	(0.387)	(0.359)	(0.429)
20-year autumn temperature SD(log)	-3.510***	-2.724**	-2.543*	-2.041*	-1.116	-2.203*
	(1.194)	(1.182)	(1.441)	(1.116)	(1.090)	(1.323)
20-year winter temperature SD(log)				0.494	3.347	3.217
				(2.190)	(2.203)	(2.567)
Male(=1)	0.043	0.023	-0.020	-0.014	-0.016	-0.031
	(0.060)	(0.058)	(0.073)	(0.055)	(0.052)	(0.071)
Age of HH	-0.001	-0.002	0.000	-0.002	-0.002	0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Household size	-0.072***	-0.087***	-0.107***	-0.063***	-0.075***	-0.101***
	(0.012)	(0.013)	(0.016)	(0.011)	(0.012)	(0.015)
Schooling year of HH	0.002	-0.005	0.002	0.001	-0.003	0.005
	(0.009)	(0.008)	(0.010)	(0.008)	(0.008)	(0.010)
Livestock ownership(=1)	0.005	0.019	0.035	-0.005	0.012	0.028
	(0.024)	(0.024)	(0.029)	(0.024)	(0.023)	(0.029)
Farm size (log)	0.018	-0.015	0.047	-0.028	-0.038	0.015
	(0.044)	(0.042)	(0.051)	(0.032)	(0.032)	(0.041)

Market access (minute)	-0.002*	-0.002	-0.001	-0.001	-0.001	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Road access (minute)	-0.001	-0.000	-0.001	-0.001	-0.000	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Irrigation(=1)	-0.123	-0.173	-0.079	-0.065	-0.096**	-0.038
	(0.111)	(0.108)	(0.131)	(0.042)	(0.041)	(0.052)
Access to agricultural extension service (=1 if yes)	0.007	-0.026	-0.022	-0.022	-0.054*	-0.030
	(0.030)	(0.030)	(0.036)	(0.031)	(0.031)	(0.039)
Year 2012	-0.432***	-0.433***	-0.440***	-0.341***	-0.256**	-0.291**
	(0.130)	(0.132)	(0.165)	(0.110)	(0.112)	(0.138)
Year 2015	-0.143	-0.215**	-0.237*	-0.113	-0.126	-0.139
	(0.108)	(0.107)	(0.136)	(0.108)	(0.104)	(0.135)
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7486	7486	7486	8033	8033	8033

Robust standard errors in parentheses
*p<0.1, ** p<0.05, *** p<0.01

Table A2: Robustness of determinants of livelihood diversification (OLS FE)

	(1) Crop diversification (Shannon)		(2) Income diversification (Shannon)	
share of households adopting crop diversification within the union	0.189***	(0.040)		
share of households adopting income diversification within the union			0.280***	(0.048)
Rainfall shock in summer	-0.019	(0.030)	0.002	(0.024)
Rainfall shock in rainy season	-0.014	(0.052)	-0.004	(0.039)
Rainfall shock in autumn	0.002	(0.007)	0.008	(0.006)
Rainfall shock in winter	0.002	(0.010)	-0.027***	(0.008)
20-year summer rainfall SD(log)	1.227*	(0.626)	0.108	(0.466)
20-year rainy season rainfall SD(log)	0.165	(0.155)	0.152	(0.119)
20-year autumn rainfall SD(log)	-0.735***	(0.185)	0.140	(0.153)
20-year winter rainfall SD(log)	-1.555**	(0.786)	-0.318	(0.588)
Temperature shock in summer	2.058*	(1.197)	1.317	(0.951)
Temperature shock in rainy season	1.641	(1.693)	0.022	(1.296)
Temperature shock in autumn	-0.663	(0.618)	0.491	(0.469)
Temperature shock in winter	0.001	(0.605)	0.417	(0.458)
20-year summer temperature SD(log)	-0.084	(0.625)	-1.328***	(0.497)
20-year rainy season temperature SD(log)	-0.481**	(0.212)	0.150	(0.166)
20-year autumn temperature SD(log)	0.926	(0.596)	-0.266	(0.483)
20-year winter temperature SD(log)	-4.484***	(1.217)	1.694*	(0.945)
Male(=1)	0.057*	(0.032)	0.052**	(0.025)
Age of HH	0.001	(0.001)	0.001	(0.001)
Household size	0.001	(0.007)	-0.006	(0.005)
Schooling year of HH	-0.003	(0.005)	-0.002	(0.004)
Farmsize (log)	0.130***	(0.013)	0.056***	(0.009)
Livestock ownership(=1)	0.015	(0.013)	0.014	(0.010)
Irrigation(=1)	0.256***	(0.021)	0.059***	(0.015)
Market access (minute)	0.001*	(0.001)	0.000	(0.000)
Road access (minute)	-0.000	(0.000)	-0.000	(0.000)
Access to agricultural extension service (=1 if yes)	0.040***	(0.014)	0.040***	(0.011)

Individual FE	Yes	Yes
Year FE	Yes	Yes
Observations	7487.000	8076.000

Robust standard errors in parentheses

*p<0.1, ** p<0.05, *** p<0.01

Table A3: Robustness of the impact of livelihood diversification (Poisson /OLS FE with IV)

	(1) HDDS	(2) Per capita food expenditure (log)	(3) HDDS	(4) Per capita food expenditure (log)
Crop diversification (Shannon)	0.060	0.226		
	(0.068)	(0.183)		
Income diversification (Shannon)			0.028	0.620***
			(0.063)	(0.227)
Rainfall shock in summer	0.006	0.006	0.000	0.071**
	(0.009)	(0.026)	(0.009)	(0.032)
Rainfall shock in rainy season	0.019	-0.059	0.013	0.042
	(0.016)	(0.044)	(0.015)	(0.054)
Rainfall shock in autumn	0.002	0.011*	0.001	0.002
	(0.002)	(0.006)	(0.002)	(0.008)
Rainfall shock in winter	-0.002	-0.011	-0.001	0.004
	(0.003)	(0.009)	(0.004)	(0.013)
20-year summer rainfall SD(log)	-0.428*	-0.615	-0.316*	-0.977
	(0.225)	(0.598)	(0.183)	(0.633)
20-year rainy season rainfall SD(log)	0.120**	-0.068	0.128***	0.056
	(0.049)	(0.136)	(0.047)	(0.166)
20-year autumn rainfall SD(log)	0.035	0.289	0.017	-0.093
	(0.081)	(0.214)	(0.059)	(0.209)
20-year winter rainfall SD(log)	0.422	0.429	0.283	0.660
	(0.280)	(0.756)	(0.232)	(0.812)
Temperature shock in summer	-0.260	3.404***	-0.150	1.327
	(0.412)	(1.166)	(0.371)	(1.365)
Temperature shock in rainy season	-0.240	-4.723***	-0.266	-1.785
	(0.525)	(1.452)	(0.497)	(1.785)
Temperature shock in autumn	-0.302	1.309**	-0.396**	1.096*
	(0.200)	(0.553)	(0.182)	(0.666)
Temperature shock in winter	0.104	-0.558	0.097	-1.571**
	(0.183)	(0.514)	(0.179)	(0.641)
20-year summer temperature SD(log)	0.100	0.151	0.169	-0.669
	(0.194)	(0.534)	(0.191)	(0.691)

20-year rainy season temperature SD(log)	0.077	0.483**	0.031	0.193
	(0.078)	(0.206)	(0.064)	(0.226)
20-year autumn temperature SD(log)	-0.413**	-3.185***	-0.363*	-1.682**
	(0.203)	(0.535)	(0.193)	(0.663)
20-year winter temperature SD(log)	0.442	-0.056	-0.037	1.187
	(0.563)	(1.473)	(0.392)	(1.341)
Male(=1)	0.022*	-0.062**	0.021**	-0.030
	(0.011)	(0.028)	(0.010)	(0.032)
Age of HH	-0.000	0.001	-0.000	0.000
	(0.000)	(0.001)	(0.000)	(0.001)
Household size	0.005***	-0.102***	0.005***	-0.084***
	(0.002)	(0.006)	(0.002)	(0.007)
Schooling year of HH	-0.000	-0.001	0.000	0.001
	(0.002)	(0.004)	(0.001)	(0.005)
Livestock ownership(=1)	0.002	0.009	0.001	0.017
	(0.004)	(0.011)	(0.004)	(0.014)
Farm size (log)	0.000	0.038	0.006	-0.001
	(0.010)	(0.026)	(0.005)	(0.017)
Market access (minute)	-0.000	-0.001**	-0.000	-0.001
	(0.000)	(0.001)	(0.000)	(0.001)
Road access (minute)	-0.000	-0.000	-0.000	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)
Access to agricultural extension service (=1 if yes)	-0.001	0.021	-0.000	-0.009
	(0.005)	(0.014)	(0.005)	(0.018)
Irrigation(=1)	-0.019	-0.067	-0.005	-0.043*
	(0.019)	(0.050)	(0.007)	(0.023)
Residual-crop	-0.058			
	(0.069)			
Residual-income			-0.018	
			(0.064)	
Individual FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	7487	7487	8076	8075

Robust standard errors in parentheses

Instrumental variables (% of diversification household within unions)

*p<0.1, ** p<0.05, *** p<0.01

Table A4: Robustness of quantile effect of livelihood diversification (Quantile FE with IV)

	(1) 25% quantile	(2) 50% quantile	(3) 75% quantile	(4) 25% quantile	(5) 50% quantile	(6) 75% quantile
Crop diversification (Shannon)	1.151	1.649*	0.968			
	(0.951)	(0.916)	(1.108)			
Income diversification (Shannon)				0.952***	0.970***	0.238
				(0.351)	(0.359)	(0.459)
Rainfall shock in summer	0.049	0.079	0.147*	0.022	0.047	0.118*
	(0.068)	(0.063)	(0.075)	(0.054)	(0.051)	(0.062)
Rainfall shock in rainy season	0.359	0.505**	0.236	0.092	0.120	-0.010
	(0.235)	(0.226)	(0.274)	(0.090)	(0.084)	(0.104)
Rainfall shock in autumn	0.015	-0.006	-0.010	0.014	-0.001	-0.004
	(0.015)	(0.015)	(0.018)	(0.013)	(0.013)	(0.016)
Rainfall shock in winter	-0.033	-0.035*	-0.016	0.009	0.015	0.007
	(0.021)	(0.020)	(0.025)	(0.021)	(0.021)	(0.024)
20-year summer rainfall SD(log)	-1.925	-2.975*	-1.767	-0.977	-1.397	-0.836
	(1.665)	(1.597)	(1.908)	(1.072)	(1.006)	(1.211)
20-year rainy season rainfall SD(log)	0.251	0.187	-0.133	0.253	0.062	-0.042
	(0.283)	(0.279)	(0.332)	(0.271)	(0.271)	(0.327)
20-year autumn rainfall SD(log)	0.140	-0.081	-0.533	0.187	0.016	-0.448
	(0.406)	(0.412)	(0.525)	(0.328)	(0.335)	(0.437)
20-year winter rainfall SD(log)	1.721	2.798	1.148	0.861	1.101	0.070
	(2.071)	(1.966)	(2.342)	(1.377)	(1.273)	(1.527)
Temperature shock in summer	-3.830	-2.149	2.204	-1.352	0.847	3.453
	(3.321)	(3.201)	(3.989)	(2.208)	(2.182)	(2.762)

Temperature shock in rainy season	6.545	10.866*	4.470	-1.950	0.496	-1.448
	(6.743)	(6.439)	(7.640)	(2.907)	(2.785)	(3.380)
Temperature shock in autumn	0.289	-0.447	2.191	0.477	0.140	1.901
	(1.160)	(1.171)	(1.383)	(1.094)	(1.084)	(1.273)
Temperature shock in winter	-1.593	-1.306	-2.463*	-1.501	-1.356	-2.228*
	(1.309)	(1.200)	(1.417)	(1.099)	(1.019)	(1.228)
20-year summer temperature SD(log)	0.612	-1.168	-2.238*	1.123	-0.535	-2.297*
	(1.112)	(1.081)	(1.283)	(1.131)	(1.117)	(1.349)
20-year rainy season temperature SD(log)	0.843**	0.459	0.204	0.463	-0.047	-0.116
	(0.429)	(0.392)	(0.458)	(0.389)	(0.361)	(0.432)
20-year autumn temperature SD(log)	-3.217***	-2.446**	-2.453*	-2.077*	-1.131	-2.266*
	(1.117)	(1.102)	(1.343)	(1.107)	(1.080)	(1.309)
20-year winter temperature SD(log)	2.879	7.644**	6.283	-1.180	1.613	2.813
	(3.678)	(3.573)	(4.210)	(2.215)	(2.215)	(2.608)
Male(=1)	0.066	0.051	-0.007	-0.006	-0.014	-0.029
	(0.056)	(0.054)	(0.069)	(0.054)	(0.051)	(0.069)
Age of HH	0.000	-0.000	0.001	-0.001	-0.002	0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Household size	-0.075***	-0.092***	-0.109***	-0.063***	-0.075***	-0.102***
	(0.013)	(0.013)	(0.017)	(0.011)	(0.012)	(0.015)
Schooling year of HH	-0.001	-0.008	0.001	0.003	-0.002	0.005
	(0.009)	(0.008)	(0.010)	(0.008)	(0.008)	(0.010)
Livestock ownership(=1)	0.012	0.030	0.042	-0.002	0.017	0.032
	(0.023)	(0.023)	(0.028)	(0.023)	(0.023)	(0.028)
Farm size (log)	0.003	-0.044	0.025	-0.012	-0.026	0.025
	(0.056)	(0.053)	(0.064)	(0.027)	(0.027)	(0.034)

Market access (minute)	-0.001	-0.001	-0.001	-0.002	-0.001	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Road access (minute)	-0.001	0.000	-0.000	-0.001	-0.000	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Access to agricultural extension service (=1 if yes)	-0.062	-0.128*	-0.084	-0.011	-0.045	-0.022
	(0.077)	(0.075)	(0.091)	(0.029)	(0.029)	(0.036)
Irrigation(=1)	0.019	0.004	0.011	-0.052	-0.085**	-0.030
	(0.037)	(0.036)	(0.046)	(0.038)	(0.037)	(0.048)
Year 2012	-0.329***	-0.250**	-0.315**	-0.329***	-0.246**	-0.285**
	(0.111)	(0.114)	(0.139)	(0.110)	(0.112)	(0.138)
Year 2015	0.014	0.024	-0.089	-0.098	-0.111	-0.123
	(0.164)	(0.156)	(0.191)	(0.108)	(0.105)	(0.136)
FE	Yes	Yes	Yes	Yes	Yes	Yes
Year dummy	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7486	7486	7486	8075	8075	8075

Robust standard errors in parentheses

Instrumental variables (% of households adopting a considered diversification within unions)

*p<0.1, ** p<0.05, *** p<0.01