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Impact of Social, Institutional and Environmental Factors on the Adoption of Sustainable Soil Management Practices: An Empirical Analysis from Bangladesh

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Abstract: This paper explores the determinants of sustainable soil management (SSM) practices among Bangladeshi paddy farmers. Relevant information from 2681 paddy farmers was extracted from the nationally representative Bangladesh Integrated Household Survey (BIHS 2018–2019) dataset. Four SSM practices were commonly practiced with 37.04% of the sampled farmers adopting at least one SSM practice. 'Use of organic fertilizer' was the most common practice, whereas the other three, viz. 'zero-tillage', 'incorporate paddy residue', and 'legume cultivation' were less practiced by the farmers. Econometric analysis revealed that differences in the farmers' socio-economic conditions, environmental and institutional settings were the main drivers of the SMM practice decisions. Climatic factors were critical in shaping the farmers' decision to adopt SSM practices. Education, access to information and extension services increased the adoption probability of SSM practices. Improved infrastructure and being located within the economically vulnerable areas (e.g., Feed the Future zone) influenced the farmers' adoption decision, but the magnitude and direction varied depending on the individual circumstances. The farmers' socio-economic conditions, e.g., assets and farm size, also had a notable influence on the adoption of SSM practices. Policy implications include strengthening extension services, incorporation of climatic information in education and dissemination of information on SSM practices, particularly to farmers living in vulnerable areas.

Keywords: sustainable soil management; adoption; climate change; socio-economic; institutional and environmental factors; Bangladesh

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1. Introduction

The rapid growth of the global population demand for food has increased and put pressure on agriculture to produce more, especially rice since this is a staple food in South Asian economies. Such increasing demand for food has resulted in increased environmental and soil degradation in many areas [1]. Soil is an essential non-renewable natural resource, which provides services vital to the ecosystem and human life and also serves as a foundation to produce all types of food derived from land [2]. A healthy soil system also reduces crop diseases and pest infestations, hence playing an important role in reducing hunger and poverty [3]. The Green Revolution (GR) played a vital role in ensuring food for the continuously increasing global population, which primarily depends on chemical inputs, high-yielding varieties and irrigation. As a consequence, the GR technologies raised serious environmental concerns, including an observation of gradual decline in the productive capacity of the soils [4,5]. This in turn aggravated the demand for essential plant nutrients, leaving agricultural lands less productive and sometimes economically unviable for cultivation [6]. There is a widespread agreement for halting soil degradation along with nurturing and unlocking the full potential of soil, so that beyond its conventionally recognized role in food production, the soil can effectively store and supply cleaner water, maintain biodiversity, sequester carbon and nitrogen from the air and increase resilience in a changing climate [2,5].

Globally, one-fifth of soil has been degraded over time by erosion, compaction and chemical deterioration, thereby reducing its productive capacity with long-lasting adverse consequences on the environment and the livelihoods of the farming population in particular [5]. The effect is enormous. An estimate by Jie et al. showed that during the last five decades of the previous century, around 11.9–13.4% of global food production was lost due to soil degradation [7]. Leon and Osorio estimated that degradation caused the Earth's soil ecosystem services to decrease by 60% between 1950 and 2010 [8]. The authors also reported soil degradation to be more severe in the tropics and sub-tropics. Lamb et al. estimated that 500 million hectares of soil in the tropics are at risk of degrading [9], whilst according to Bini 33% of the global land surface is affected by some type of soil degradation [10]. Africa, followed by Central America and Asia, top the list [7]. In South Asia, around 140 million ha of agricultural land is experiencing soil erosion, declining soil fertility, waterlogging and groundwater depletion [11]. A study by the FAO estimated the severity and costs of land degradation in South Asia to be worth at least USD 10 billion annually, which is equivalent to 2% of the Gross Domestic Product (GDP) of the region [12].

A holistic soil management approach, including sustainable soil management (SSM), is considered as the engine for increasing agricultural productivity by raising resource use efficiency and making agriculture environmentally compatible [13,14]. Sustainable soil management refers to the operations, practices and treatments to maintain and enhance soil performance without impairing biodiversity. Provisioning nutrients for plant production, ensuring water quality and atmospheric greenhouse gas composition maintenance are particular concerns in SSM [2]. In order to sustain agricultural production, maintaining good biophysical condition of the soil is essential, which is possible through appropriate agronomic practices including SSM [15,16]. The literature emphasizes the beneficial impacts of SSM on farm productivity. For instance, legumes can counter declining productivity caused by continuous cereal-based cropping [17], while the use of organic manure can increase productivity [18–21]. Sustainable soil management is the key to adapt and mitigate climate change effects and maintain sustainable agricultural production [22,23], while ensuring environmental sustainability [24]. Sustainable soil management also plays pivotal roles in attaining the Sustainable Development Goals (SDGs) of the United Nations, notably SDG 2 (i.e., Zero Hunger) and SDG 15 (i.e., Life on Land), both of which mention sustainable soil use and reduction of soil degradation as important considerations. Furthermore, SSM indirectly assists to achieve SDG 1 (i.e., No Poverty), SDG 12 (i.e., Responsible Consumption and Production), SDG 13 (i.e., Climate Action) and SDG 14 (i.e., Life Below Water) [3,25,26].

In Bangladesh, 74.2% of the land suffers from nutrient deficiency and 56.7% of the land is affected by soil acidity [27]. However, while organic matter in the soil in Bangladesh increased from 2010 to 2020, 78.9% of the area still has low organic matter [27,28]. The major drivers of soil organic matter depletion in the country are intensive tillage, puddling, soil erosion, soil salinity and acidity, deforestation, nutrient leaching and minimum manure application, etc. [28–31]. Moreover, the availability of plant nutrients including phosphorus, potassium, sulfur, zinc, boron, calcium and magnesium in the soils of Bangladesh has reduced during the last decade [28]. Soil degradation is linked with food security, climate change vulnerability and poverty [32] and the World Commission on Environment and Development suggested a "vicious cycle" between poverty and degradation as poor people, who are largely agriculturally based, over-exploit the available natural resources for their survival [33].

Despite of the importance of addressing the soil degradation issues and availability of technologies, soil degradation as a global phenomenon has become more critical than ever in the 21st century [34]. Soil sustainability is substantially affected by the management decisions made by farmers [35]. The actual farm-level adoption decision comprises a wide range of complex and interconnected socio-political, institutional, environmental and climatic issues [36–39], which are time-variant and context-specific, particularly when the climate is changing [40]. Such interdependencies between natural and anthropogenic processes make soil management studies and planning complex. This ultimately highlights the importance of incorporating social science in soil science research, which is still a rare combination to find [3,41] and with very few exceptions. For example, Bennett et al. attempted to explain SSM practices in New Zealand through the farmers' beliefs, attitudes and motivations [42]. They used both quantitative and qualitative types of soil condition indicators. While the former category was derived through soil testing, the latter was derived from the farmers' qualitative assessment. Since soil testing requires time and cost, the study only included information from 14 farmers and hence there remain concerns about the generalization of the findings. Any SSM-related study faces such trade-offs, as using both soil science- and social science-related indicators in larger sample sizes is always difficult. Alternatively, since the qualitative indicators are subject to the individual farmer's judgments where an individual's knowledge, attitude and beliefs have a role, there always remains a concern about the unbiasedness of the estimated indicators. Moreover, such qualitative analysis can be practiced only with farmers having some prior knowledge about the biophysical and chemical parameters of the soil.

Despite the amount of work on soil management and conservation technology adoption, the majority of the studies are experimental research exploring the suitability and impact of different SSM practices [17,19–21], which are difficult to generalize and hence rarely used in the policy arena. To the best of the knowledge of the authors, no study specific to Bangladesh has specifically explored farm-level adoption considering the socio-economic and institutional determinants of SSM, although in some SSM is considered under climate-smart technology e.g., [43]. A few studies focusing on other countries and regions are available; however, the available ones have limitations, as some identify determinants of SSM practices without distinguishing between technologies e.g., [44–46]. Such 'one size fits all' types of approaches should be avoided as a farmer may substitute or complement between technologies. The available literature lacks a holistic approach while picking the determinants of adoption. For example, despite the noted disputed role of environmental and climatic factors in agriculture, the role of climate hazards and other factors is still missing in the literature. Furthermore, almost all of the previous studies only consider adoption in a particular agro-ecology [47–49], while policies are designed at a national level.

Therefore, taking account of these research gaps in the literature, the main objectives of this study are to: (a) examine the various SSM adaptation practices that farmers undertake; (b) identify the determinants of undertaking the SSM practices, while allowing farmers to adopt any one or multiple practices simultaneously; and (c) explore whether synergy and/or competition exists between various the SSM adoption practices undertaken by the farmer to combat climate change effects. This study will address these global research questions using a nationally representative farm-level survey of Bangladesh, which is one of the most vulnerable countries to climate change [50] and where agriculture contributes around one-sixth of the GDP and around 40% of people earn their livelihood from the sector [51]. In Bangladesh, an increasing trend in soil fertility and health degradation is observed for which both human interventions and natural causes are responsible, although the major responsibility is anthropometric. Some important related factors are the intensified use of crop lands, cultivation of modern crop varieties (HYVs and hybrids), soil erosion, soil salinity and acidity, deforestation, nutrient leaching and minimum manure application [28].

2. Methodology

2.1. The Theoretical Framework for Understanding Farmers' SSM Adoption Decisions

Several competing models or approaches are available to understand the adoption decision process of farmers. We adopt the 'action theory' approach [52] that describes a farmer's adoption decisions when the environment is changing. In the action theory, there are some stimuli which act as the stimulator to take action. A stimulus is defined as a change in the biophysical variables and also refers to an abrupt, large-scale event in the Earth's system. In our case, the deteriorating soil fertility and changing climate work as the stimuli for adopting SSM. Adaptation occurs only when the stimulus affects the exposure unit. The biophysical systems (e.g., farm) and social entities (e.g., farmers and households) where adaptation takes place are termed the receptor. The individual or collective that exercises the response is called the operator. Here, the farm and farm household are both exposure units; receptors and operators at the same time because they are affected by the stimulus, and also adopters of the SSM practices. To adopt, an operator requires different resources (e.g., human and natural capital, social networks, access to institutions and information, etc.), which are termed the means. Actions also depend on other additional constraints and resources that are beyond the control of the operator, which are referred to as the conditions. As different farmers can take different actions while facing the same stimulus, the differences in the actions can be explained through the differences in the means they possess and the conditions they face. The farmers' awareness and attitude are critical here as Cary and Wilkinson argued that perception can lead to the recognition of a soil condition problem, and a keen farmer will ultimately have a sharper perception when the problem is analyzed more closely [53]. Ajzen's integrated model of behavior describes the determinants of farmer behavior, including their salient beliefs and evaluations of management practices, as well as beliefs and motivations with respect to normative influences (referents) and perceived constraints on behavior [54]. Incorporating these studies from the literature, we attempt a schematic representation in Figure 1 for understanding the farmers' SSM adoption behavior.

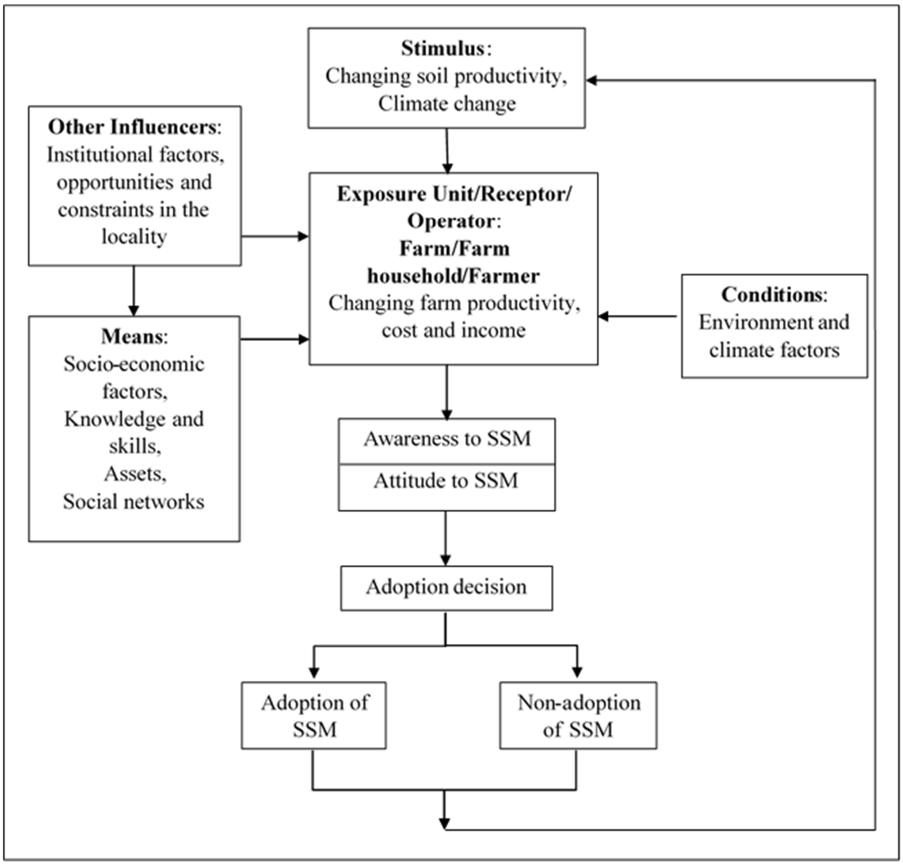

Figure 1. Schematic representation for understanding the farmers' sustainable soil management adoption behavior. Note: Developed based on Eisenack and Stecke, Reid et al., Neupane et al. and Harris and Bezdicek [52,55–57].

2.2. Data

This study uses data from multiple sources. Data about the farmer's SSM practices and possible farm- and farmer-specific determinants were collected from the third round of the Bangladesh Integrated Household Survey 2018–2019 (BIHS)[1] of the International Food Policy Research Institute (IFPRI) [58]. Climate vulnerability-related data were collected from different government sources. The BIHS is representative of rural Bangladesh, which has data on a wider dimension of livelihood, including different aspects of agricultural production covering all three crop growing seasons from December 2017 to November 2018. This dataset contains information collected from 5604 households belonging to 325 primary sampling units (PSUs). Among them, 2681 households cultivated paddy during the reference period. The SSM practices of the paddy farmers are the focus of this study because paddy occupies around 75% of total cropped area and 80% of the total irrigated area in Bangladesh [59]. In addition, vulnerability data on salinity, rainfall, and storms and cyclones were obtained from the vulnerability maps developed by the Bangladesh Agro-Meteorological Information Portal[2], Department of Agricultural Extension [60]. Information about drought was collected from the Ministry of Disaster Management and Relief [61][3]. Table 1 lists all of the variables used in this study and their sources.

2.3. Econometric Analysis to Identify the Determinants of SSM Practice Adoption

To understand a farm household's SSM adoption decision, a multivariate probit (MVP) model was developed, which can jointly identify the determinants of the identified SSM practices. The MVP model also provides a test of the inter-relatedness (i.e., whether various SSM supplement or substitute each other) of the decision-making process among different SSM adoption. The model does so by providing an estimate of the correlation between the error terms of the individual univariate models (i.e., individual uptake model) nested in the multivariate model [62].

Sustainable soil management comprises management practices including, but not limited to, the use of organic manure, the cultivation of legume crop, growing cover crop, crop rotation, mulching, zero-tillage, minimal tillage and crop residue amendment [63,64]. In this study, we considered four SSM practices which were commonly practiced by the sample of paddy farmers, namely, 'zero-tillage', 'use of organic fertilizer', 'incorporate paddy residue' and 'legume cultivation'. The MVP consists of a separate probit equation for each of the adopted SSM, where the value of the dependent variable y_m is 1 if the farmer adopted that m^{th} practice and 0 otherwise. The MVP model exploring the four SSM adoption decisions can be written as [65]:

$$y_m^* = x_m'\beta_m + \varepsilon_m,\ y_m = 1\ if\ y_m^* > 0,\ 0\ otherwise,\ m = 1,\ldots,4$$

$$\begin{aligned} E[\varepsilon_m|x_1,\ldots,x_4] &= 0; \\ \mathrm{Var}[\varepsilon_m|x_1,\ldots,x_4] &= 1; \\ \mathrm{Cov}\left[\varepsilon_j,\varepsilon_m\middle|x_1,\ldots,x_M\right] &= \rho_{jm}; \\ (\varepsilon_1,\ldots,\ \varepsilon_m) &\sim N_M[0,R] \end{aligned} \quad (1)$$

The joint probabilities of the observed events $[y_{i1}, y_{i2}, \ldots, y_{iM}|x_{i1}, x_{i2}, \ldots, x_{iM}]$, $i = 1,\ldots,n$, that form the basis for the likelihood function are the M-variate normal probabilities:

$$L_i = \Phi_M\left(q_{i1}x_{i1}'\beta_1,\ \ldots, q_{iM}x_{iM}'\beta_M, R^*\right) \quad (2)$$

where $q_{im} = 2y_{im} - 1$ and $R_{jm}^* = q_{ij}q_{iM}\rho_{jm}$

where ρ_{jm} is the correlation between ε_j and ε_m. The distributions are independent if and only if $\rho_{jm} = 0$. Then equations for farmers facing m adoption choices can be written as:

Table 1. Description of the explanatory variables used in the MVP model.

Variables	**Definition and Measurement**	**Data Source**
Dependent variables		
Organic fertilizer	Dummy; 1 if the household used manure and/or compost in their paddy field, 0 otherwise	IFPRI (2020)
Paddy residue	Dummy; 1 if the household incorporated paddy residue in their paddy field either by burning or ploughing, 0 otherwise	
Legume cultivation	Dummy; 1 if the household cultivated legumes in their paddy field, 0 otherwise	
Zero-tillage	Dummy; 1 if the household practiced zero-tillage in their paddy field, 0 otherwise	
Explanatory variables		
Household's socio-economic and demographic factors		
Gender	Dummy; 1 if the main decision-maker in the household was female, 0 otherwise	IFPRI (2020)
Age	Age of the household head (complete years)	
Education	Formal schooling completed by the most educated household member	
Primary	Dummy; 1 if the completed years of formal schooling was >0 and ≤5, 0 otherwise	
Secondary	Dummy; 1 if the completed years of formal schooling was >5 and ≤10, 0 otherwise	
Higher secondary	Dummy; 1 if the completed years of formal schooling was >10 and ≤16 (including diploma/vocational degrees), 0 otherwise	
Graduation and above	Dummy; 1 if the completed years of formal schooling was >16, 0 otherwise	
Dependency ratio	Ratio of economically inactive household members to total household members	
Assets	Market value of agricultural and non-agricultural productive assets (excluding land) owned by the household ('000 USD/per capita) [4] during 2017–2018	
FtF zone	Dummy; 1 if the households lived in the Feed the Future zone (FtF) zone [5], 0 otherwise	
Farm characteristics		

Table 1. Cont.

Variables	**Definition and Measurement**	**Data Source**
Farm size	Total area planted under different crops (Ha)	IFPRI (2020)
Loam soil	Dummy; 1 if any portion of the household-owned land was loam soil, 0 otherwise	
Multiple irrigation sources	Dummy; 1 if the household had access to multiple irrigation water sources including surface and ground water, 0 for a single water source	
Rice-fish culture	Dummy; 1 if the household practiced rice-fish culture in the same plot, 0 otherwise	
Livestock	Dummy; 1 if the household had any livestock in their house, 0 otherwise	
Access to extension service, infrastructure and ICT		
Synthetic fertilizer training	Dummy; 1 if the household received training on use of chemical fertilizer in paddy production, 0 otherwise	IFPRI (2020)
Advice on fertilizer	Dummy; 1 if the household received fertilizer-related advice from government extension/NGOs officials, 0 otherwise	
Advice on soil	Dummy; 1 if the household received soil-related advice from government extension/NGOs officials, 0 otherwise	
Concrete road	Dummy; 1 if the household had any access to concrete road from their house, 0 otherwise	
Mobile banking	Dummy; 1 if the household used mobile banking facilities, 0 otherwise	
Climate hazard variables		
Flood depth	The usual flood depth during monsoon/flood season, in case of multiple plots the plot with maximum depth was reported (0 if not flooded) (feet)	IFPRI (2020)
Drought vulnerability	Dummy; 1 if the household was from drought-prone region, 0 otherwise	MoDMR, 2013
Salinity vulnerability	Dummy; 1 if household was from salinity affected area, 0 otherwise	DAE, 2020
Rainfall vulnerability	Dummy; 1 if household was from rainfall risk region, 0 otherwise	DAE, 2020
Storm and cyclone vulnerability	Dummy; 1 if the household was from storm and cyclone risk area, 0 otherwise	DAE, 2020

$$\begin{cases} y_1^* = x'\beta_1 + \varepsilon_1,\ y_1 = 1\ if\ y_1^* > 0,\ 0\ otherwise \\ y_2^* = x'\beta_2 + \varepsilon_2,\ y_2 = 1\ if\ y_2^* > 0,\ 0\ otherwise \\ \vdots \\ y_m^* = x'\beta_m + \varepsilon_m,\ y_m = 1\ if\ y_m^* > 0,\ 0\ otherwise \end{cases} \quad (3)$$

The stochastic component (ε_m) takes care of all of the unobservable factors that may explain the marginal probability of deciding to adopt practice m. Each ε_m is drawn from an M-variate normal distribution with zero conditional mean and variance normalized to unity, where $\varepsilon_m \sim N(0, \sum)$, and the covariance matrix $\sum$ is given by:

$$\sum = \begin{bmatrix} 1 & \rho_{12} & . & . & . & \rho_{1m} \\ \rho_{21} & 1 & . & . & . & \rho_{2m} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ \rho_{m1} & \rho_{m2} & . & . & . & 1 \end{bmatrix} \quad (4)$$

The off-diagonal elements of the covariance matrix (ρ_{jm}) are of our particular interest. The elements represent the unobserved correlation between the stochastic components of the j^{th} and m^{th} SSM adoption decision. The marginal probability of observing m^{th} SSM adoption can be expressed as:

$$\text{Prob}(y_m = 1) = \Phi(x'\beta_m)\ for\ all\ m = 1 \quad (5)$$

where $\Phi(.)$ is the cumulative density function (CDF) of the standard normal dsitribution. The joint probabilities of observing all possible types of SSM adoption comes from the M-variate standard normal distribution:

$$\text{Prob}(y_1 = 1, \ldots, y_m = 1) = \Phi_m(x'\beta_1, \ldots, x'\beta_m; \sum) \quad (6)$$

where x_i are different explanatory variables, including both the farm-level socio-economic and biophysical factors that may influence a farmer's adoption decisions. The detailed measurement techniques of all of the variables are presented in Table 1.

3. Results

3.1. Adoption of SSM Practices

Table 2 illustrates the adoption rate of the different SSM technologies practiced by the paddy farmers. Around 37% of the farmers adopted any of the four identified SSM technologies. Among them, 'use of organic fertilizer' was the most common and was adopted by 28% of the paddy growers. The adoption of the other three practices was sporadic. Most of the adopters (94.26%) adopted a single technology and none adopted all four of the technologies simultaneously (Figure 2).

Table 2. Adoption of sustainable soil management practices by paddy farmers.

SSM Practices	Percentage of Farmers
Use of organic fertilizer	28.38
Incorporate paddy residue	4.70
Legume cultivation	3.80
Zero-tillage	2.31
Any of the above practices	37.04

3.2. Summary Statistics of the Explanatory Variables Used in the Econometric Analysis

The proportion of female-headed households among the adopters of 'incorporate paddy residue' was almost double than was observed for the non-adopters. With a growing educational status of the most educated household member, the number of cases with a significant difference between adopters and non-adopters was progressively decreasing. For the 'graduate and over' category, the differences were not significant for any of the practices. The households in higher proportions in the FtF zone adopted 'zero-tillage' and 'legume cultivation', while the opposite was observed for the other two practices. Except for 'zero-tillage', the adopters and non-adopters of the other three practices had significant differences in the value of the assets they owned, although there was no trend. Compared to the non-adopters, the adopters of 'use of organic fertilizer' had a significantly higher proportion of access to all of the services and facilities mentioned in the category of variables used to represent access to extension, infrastructure and information and communications technology (ICT). Similarly, significant differences were observed between the adopters and non-adopters of 'use of organic fertilizer' across all of the climate hazard variable with no trend (Table 3).

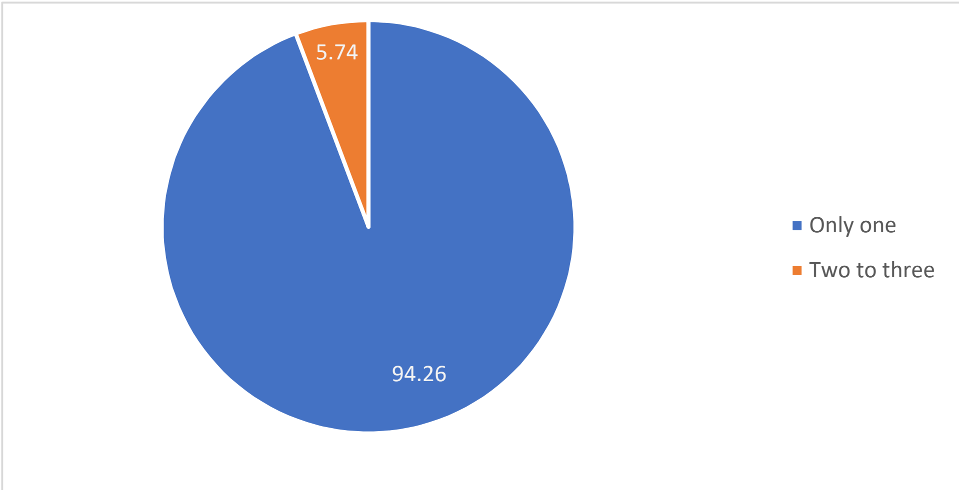

Figure 2. Number of sustainable soil management practices adopted by the adopter farmers.

Table 3. Summary statistics of the variables used in explaining adoption of sustainable soil management practices.

Variables	Use of Organic Fertilizer		Incorporate Paddy Residue		Legume Cultivation		Zero-Tillage	
	Adopter	Non-Adopter	Adopter	Non-Adopter	Adopter	Non-Adopter	Adopter	Non-Adopter
Household's socio-economic and demographic factors								
Gender	0.04	0.08 ***	0.13	0.07 **	0.09	0.07	0.08	0.07
Age	47.94	47.86	48.65	47.85	50.99	47.76 **	49.33	47.85
Education (base no formal schooling)								
Primary	0.12	0.18 ***	0.23	0.16 **	0.15	0.16	0.31	0.16 ***
Secondary	0.55	0.49 ***	0.47	0.51	0.5	0.51	0.35	0.51 **
Higher secondary	0.11	0.1	0.14	0.1	0.16	0.10 **	0.11	0.1
Graduation and above	0.05	0.05	0.04	0.05	0.06	0.05	0.08	0.05
Dependency ratio	0.73	0.75 ***	0.74	0.75	0.74	0.75	0.73	0.75
Assets	0.31	0.24 ***	0.17	0.27 ***	0.33	0.26 ***	0.26	0.27
FtF zone	0.09	0.23 ***	0.13	0.19 *	0.38	0.18 ***	0.46	0.18 ***
Farm characteristics								
Farm size	0.59	0.45 ***	0.51	0.49	0.46	0.49	0.32	0.49 ***
Loam soil	0.24	0.26	0.18	0.26 **	0.24	0.25	0.27	0.25
Multiple irrigation sources	0.43	0.31 ***	0.42	0.34 *	0.25	0.35 **	0.43	0.35
Rice-fish culture	0.02	0.01	0.04	0.01 ***	0	0.01	0.05	0.01 **
Livestock	0.9	0.82 ***	0.73	0.85 ***	0.88	0.84	0.85	0.84

Table 3. *Cont.*

Variables	Use of Organic Fertilizer		Incorporate Paddy Residue		Legume Cultivation		Zero-Tillage	
	Adopter	Non-Adopter	Adopter	Non-Adopter	Adopter	Non-Adopter	Adopter	Non-Adopter
Access to extension service, infrastructure and ICT								
Synthetic fertilizer training	0.06	0.03 ***	0.02	0.04	0.08	0.03 **	0.02	0.04
Advice on fertilizer	0.22	0.16 ***	0.13	0.18	0.17	0.18	0.19	0.17
Advice on soil	0.06	0.03 ***	0.05	0.04	0.05	0.04	0.06	0.04
Concrete road	0.42	0.52 ***	0.38	0.49 **	0.79	0.48 ***	0.4	0.49
Mobile banking	0.5	0.44 ***	0.45	0.46	0.41	0.46	0.47	0.46
Climate hazard variables								
Flood depth	1.93	2.68 ***	2.46	2.47	2.24	2.48	2.67	2.46
Drought vulnerability	0.55	0.36 ***	0.24	0.43 ***	0.46	0.41	0.29	0.42 *
Salinity vulnerability	0.11	0.31 ***	0.15	0.26 ***	0.59	0.24 ***	0.56	0.25 ***
Rainfall vulnerability	0.97	0.93 ***	0.95	0.94	0.9	0.95 **	0.91	0.94
Storm and cyclone vulnerability	0.43	0.70 ***	0.42	0.63 ***	0.91	0.61 ***	0.75	0.62 **
N	761	1920	126	2555	102	2579	62	2619

Note: ***, **, and * indicate the mean differences between the adopters and non-adopters are significant at 1%, 5%, and 10% levels, respectively.

3.3. Determinants of Different SSM Practices

The marginal effects of the explanatory variables used in explaining the paddy farmers' SSM adoption decisions are presented in Table 4. The model diagnostics at the bottom of the table showing different test statistics argue that the model is a good fit. The likelihood ratio test rejected the null hypotheses that 'correlations of the error terms across four equations are jointly zero', which justified the superiority of our chosen approach as compared to those available in the literature. The effect of different farm- and farmer-specific socio-economic and institutional variables used in the model varied across the SSM practices. This is also the case with the climatic factors, although the climatic variables were observed to have a more dominant effect on the adoption decisions.

3.3.1. Use of Organic Fertilizer

The adoption probability of the SSM practice 'manure and/or compost' was higher for households where the head was a male and the most educated household member had a secondary level of education. With increasing farm size and value of the productive assets, the probability of adopting 'use of manure and/or compost' increased, while the probability reduced when the dependency ratio reduced. The households located in the FtF zone were less likely to adopt 'use manure and/or compost' as a SSM strategy. The households with access to multiple irrigation sources, using mobile banking, rearing livestock and practicing rice-fish culture were more likely to adopt 'use of manure and/or compost'. Training on synthetic fertilizer and advice on soil significantly contributed to a household's probability of adopting 'use of manure and/or compost'. With increasing flood depth, the probability of adoption reduced. In the face of drought vulnerability, a household's probability of adopting 'use of manure and/or compost' increased, while the opposite was true for households facing salinity, and storm and cyclone vulnerability.

3.3.2. Incorporate Paddy Residue

The female-headed households and households where the highest educated member studied to higher secondary level were more likely to adopt 'incorporate paddy residue' than their counterparts, who had male heads and where none of the household members had any formal education. With the increasing value of productive assets, a household's probability of adopting 'incorporate paddy residue' reduced. The households practicing rice-fish culture were more likely to adopt the practice, while the opposite was true for the households who had livestock. The households who received advice on fertilizer and soil were more likely to 'incorporate paddy residue' than their counterparts who did not receive any such advice. The adoption probability was lower for households living in areas vulnerable to drought, storm and cyclone.

Table 4. Marginal effects of the variables used in explaining adoption of sustainable soil management practices and synergies among the sustainable soil management practices (MVP model).

Variables	Use of Organic Fertilizer	Incorporate Paddy Residue	Legume Cultivation	Zero-Tillage
Household's socio-economic and demographic factors				
Gender	−0.07 **	0.02 **	0.02	−0.002
Age	0.01	0.00	0.0004 *	0.0001
Education (base no formal schooling)				
Primary	−0.04	0.02	0.01	0.02 **
Secondary	0.03 *	0.01	0.004	−0.01
Higher secondary	0.02	0.03 **	0.02 *	−0.003
Graduation and above	−0.01	−0.01	0.003	0.001
Dependency ratio	−0.19 ***	−0.03	0.004	−0.02
Assets	0.09 ***	−0.09 ***	0.03	0.003
FtF zone	−0.09 ***	0.02	−0.01 **	0.02 **
Farm characteristics				
Farm size	0.03 **	0.01	−0.01	−0.03 ***
Loam soil	−0.01	−0.01	0.001	−0.002
Multiple irrigation sources	0.05 ***	0.01	0.001	0.02 **
Rice-fish culture	0.15 **	0.07 ***	0.00001	0.04 **
Livestock	0.11 ***	−0.02 **	0.01	0.003
Access to extension service, infrastructure and ICT				
Training on synthetic fertilizer	0.10 ***	−0.02	0.03 *	−0.02
Advice on fertilizer	−0.02	0.03 **	0.003	0.001
Advice on soil	0.08 **	0.04 **	0.0001	0.02
Concrete road	−0.02	−0.01	0.04 ***	−0.01 *
Mobile banking	0.03 **	0.01	−0.01	0.004
Climate hazard variables				
Flood depth	−0.01 ***	−0.001	0.0001	0.001
Drought vulnerability	0.11 ***	−0.04 ***	0.009	−0.01 **
Salinity vulnerability	−0.08 ***	−0.02	0.04 ***	0.02 **
Rainfall vulnerability	0.07	−0.01	−0.01	0.01
Storm and cyclone vulnerability	−0.12 ***	−0.04 ***	0.03 ***	−0.004
Constant	−0.63 **	−0.85**	−3.19 ***	−2.12 ***
Model diagnostics				
Wald χ^2 (96)	623.04 ***			
Log-likelihood	−2454.67			
LR test (H_0: $\rho_{12} = \rho_{13} = \rho_{14} = \rho_{23} = \rho_{24} = \rho_{34} = 0$)	18.00 ***			
N	2681			
Correlation between the error terms				
Incorporate paddy residue	−0.06			
Legume cultivation	−0.14 ***	−0.08		
Zero-tillage	0.13 ***	−0.04	−0.05	

Note: ***, **, and * indicate a significant level of 1%, 5%, and 10%, respectively.

3.3.3. Legume Cultivation

With increasing age of the household head, a household's probability of adopting 'legume cultivation' increased. The households where the most educated member had a higher secondary level of education were more likely to practice 'legume cultivation' than their counterparts with no formal education. The households living in the FtF zone were less likely to cultivate legumes, while those living in the salinity-vulnerable areas were more likely to adopt. Advice on fertilizer increased a household's probability to cultivate legumes. The households who were directly connected through concrete roads were more likely to cultivate legumes.

3.3.4. Zero-Tillage

Compared to the households with no educated members, the households where the highest educated member had a primary level of education were more likely to practice 'zero-tillage'. The negative coefficient associated with the variable farm size argued that with increasing farm size the probability of adopting 'zero-tillage' reduced. The households with access to multiple irrigation sources were more likely to practice 'zero-tillage' compared to their counterparts who had access to multiple sources. Practicing rice-fish culture increased a household's probability of adopting 'zero-tillage'. The households who were directly connected through concrete road were less likely to practice 'zero-tillage'. The analysis with the climate hazard variables showed that 'zero-tillage' adoption probabilities were higher in areas vulnerable to salinity, but lower in drought-vulnerable areas.

3.4. Synergies in the Adoption of SSM Practices

The lower part of Table 4 illustrates the correlations between the error terms of each pair of equations, which refer to the synergies between the adoption decision of the two SSM practices. The positive correlation between 'zero-tillage' and 'use of manure and/or compost' argued that the adoption of any of the two practices enhanced the probability of adopting another one. However, the errors of the equations 'legume cultivation' and 'use of manure and/or compost' were negatively correlated, which implied that a farmer practicing either of the two practices was less likely to practice the other.

4. Discussion

The deteriorating soil fertility, whether caused by human interventions (i.e., intensive agriculture, soil pollution from industrial sector) and/or natural reasons (i.e., climate change-induced desertification and salinization) as a stimulus may motivate farmers towards SSM. The stimulus is likely to be more effective for farmers observing substantial gradual decline in soil fertility and a consequent decrease in crop yields, for which their available practices are not adequate to compensate. In such a situation, depending on their available natural resource base and other conditions, a farmer may consider SSM practices. The ungrounding human and non-human settings and institutions can influence the decision-making process.

The estimated adoption rate of SSM practices, compared to that reported in previous studies on climate change adaptation in Bangladesh e.g., [43], was quite low (37% farmers). Since the benefits from SSM practices may not be observed immediately, rather these practices contribute to improving soil health and the full benefits can be yielded over the long term, farmers, particularly the tenants, may not be interested in adoption. Rather, the practices that can result in immediate benefits (e.g., increased chemical input use) and are capable of addressing immediate climatic challenges, such as seasonal rainfall and temperature vulnerability (e.g., short duration and heat tolerant crop varieties) and climatic hazards (e.g., stress tolerant crop varieties), are likely to have relatively higher adoption rate. Though these practices can be simultaneously adopted with SSM practices, a farmer may avoid multiple practices considering the implications on time, effort and investment. Among the four identified SSM practices, namely 'use of organic fertilizer', 'incorporate paddy residue', 'legume cultivation' and 'zero-tillage', 'use of organic fertilizer' was the most commonly practiced. Organic fertilizer has been promoted in Bangladesh for several decades through intensive farm level advice, training and other extension services by government extension services and other non-governmental organizations (NGOs). However, Anik et al. cautioned that farmers applying organic fertilizer on top of inorganic fertilizer without considering plant crop requirements can ultimately contribute to higher nitrous gas emissions [43]. The common practice in Bangladesh is to incorporate paddy residue through burning, though few farmers plough for that purpose. Although burning may have environmental consequences, farmers practice this to avoid the cost of ploughing with residue. One may be suspicious of the very low estimated proportion of farmers cultivating legumes, when legumes are commonly grown in Bangladesh particularly in the highlands and in the dry season. However, we considered the plots under the paddy, which are generally lowlands as water availability can be eased. Moreover, incorporating legumes in the cropping calendar in between monsoon and dry-winter paddy is not always feasible.

Along with an increase in age, farmers gain experiences about various agricultural practices [66]. An older farmer may become more cautious than the younger ones about the negative implications of rice monoculture on soil health. These negative implications are likely to motivate them towards legume cultivation, as rotating between paddy and legumes enhances the soil health through nitrogen fixation. Nyangena also noted that older farmers invest more in soil and water conservation practices [67].

In many instances, the literature reported education as an important factor influencing SSM adoption decisions. Marenya and Barrett corroborated that the minimum of secondary education for the household head has a significant positive effect on the integrated natural resource management adoption in western Kenya [68]. Education provides a favorable disposition to the respondents about various ideas and skills related to land management activities to improve the crop production [64] so that the higher educational attainment of farmers and other members makes them better informed and willing to adopt sustainable land and soil management practices [69].

Gender differences in climate change adaptation decisions, which argues for practices focusing on women, is a well-highlighted issue in the literature. Several factors, including differences between women and men in knowledge, ownership and access to both natural and financial resources and position in the society, are critical to understanding the role of gender. While in the context of China, Jin et al. noted males more proactively adopting new technologies and making necessary investments [70], while Oyawole et al. observed that women have a higher likelihood of adopting green manure and agroforestry [71]. These differences argue that given the nature of the technology and the context, the dominant role of males and females may vary.

Marenya and Barrett reported that the number of adults in households who might participate in various economic activities positively affects the integrated natural resource management adoption [68]. Assets may assist farmers to invest in SSM technologies for improving degraded soil. The literature reports a higher likelihood of adopting fertilizer and other soil management practices for households having more farm assets [44] and more income [45]. Additional income or assets provide farmers with more room to invest in soil conservation practices [72]. Gikonyo et al. argued that the investment in climate-smart technology (CSA) can be hampered by financial constraints where the farmers' own income and savings can contribute to easing the constraints [73]. As larger farms are likely to own more livestock, with increasing farm size a farm's likelihood of practicing 'use of organic fertilizer' also increases. Moreover, as the large farms are more likely to own and/or have access to 'machinery required for land preparation', these households are less likely to adopt 'zero-tillage'.

Similar causations can be suggested to explain the positive coefficients with the variables 'livestock' and 'rice-fish culture', as households with these income sources can easily be assumed to have higher income than their counterparts who do not have these income sources. The integrated rice-fish culture provides a higher yield and profit than rice monoculture [74,75]. Furthermore, the farmers who adopt integrated rice-fish culture can be argued to have better knowledge about resource utilization and various sustainable practices. All of these factors may trigger the farmers to invest in SSM.

The households owning livestock are more likely to adopt SSM practices. Home-supplied livestock waste as a source of organic manure contributes to soil fertility improvement, while the households that do not own cattle, poultry or other livestock have limited access to animal manure [76], therefore having a low probability of adopting 'use of organic fertilizer'. A farm household with livestock can use the paddy residue left in the field as feed, and hence may not be interested in incorporating these in the fields.

The goal of the FtF program in Bangladesh is to support inclusive and sustainable agriculture-led growth and strengthen resilience in certain areas that are vulnerable to poverty, hunger and malnutrition [77]. This program ascertained that the farmers in these areas are resource-poor and as a consequence, are less capable of adopting more sustainable farm technologies like 'use of organic fertilizer' and 'legume cultivation'. Alternatively, a major motivation for adopting 'zero-tillage' technology is to reduce the cost; the farmers in these areas showed higher likelihood of adopting the technology than farmers from other parts of the country. Since having multiple irrigation sources reduces water-related uncertainty in production, a farmer may find interest in investing in other technologies. This risk aversion characteristic of farmers can help the adoption of new technologies [78] such as 'use of organic fertilizer' and 'zero-tillage'.

Extension services in the form of training and information play a significant role in farming decisions [44,69,79]. In line with previous studies, the mvprobit model estimate showed that the training on synthetic fertilizer and advice on soil and fertilizer increased the likelihood of adopting different SSM technologies. Similarly, farmers who used mobile banking were likely to be more oriented with ICT technologies and could access information; they were more likely to adopt 'use of organic fertilizer' (Table 4). Through training on chemical fertilizers, farmers could access the necessary information which made them aware of the associated benefits of balanced fertilization and the adverse impact of over-fertilization. As a result, they understood the importance of soil health improvement and invested in SSM practices. Darkwah et al. also opined that formal training on maize production has a positive association with the number of soil and water conservation practices adopted by the farmers in Ghana [63]. Furthermore, contact with an extension agent is an important information source for improved agricultural production and management practices [80], which strengthens the farmer's agricultural knowledge base [81]. Here, soil-related advice from government extension officers and NGOs enhanced the farmer's preferences to adopt SSM. When farmers received any recommendation about soil type, management and treatment, it encouraged them to take preferable action for increasing soil fertility in the long run with SSM. Thus, gradual advances in technology development and continuous retraining of farmers are essential for the persistent adoption of sustainable agricultural technologies [66].

Improved infrastructure is critical as it enables a farmer to choose the market likely to be most efficient and thus can affect a farmer's crop choices. A farm household with access to a concrete road was more likely to cultivate legumes than food crops as the access to market was likely to be easier than with limited access. The importance of appropriate adaptation practices to mitigate climatic challenges on agriculture and livelihood is well argued and highlighted in the literature e.g., [82]. In line with the literature reporting notable influences of climatic factors and events on farmers' crop choices, land use pattern and farming practices [52,83,84], we observed significant roles of the climate hazard variables in both the descriptive and econometric analysis. However, the directions were not unidirectional; rather they varied according to the type of vulnerability, which was also highlighted in the literature demanding climate change adoption research to be region and context-specific [40]. For instance, a household that was vulnerable to drought was more likely to adopt 'use of chemical fertilizer', while the same household was less likely to adopt 'incorporate paddy residue' and 'zero-tillage'.

Agriculture is the first economic sector to be affected by drought because of soil degradation [61]. Drought makes soil tough for crop production as it relates to moisture deficit in the soil; mostly in the topmost 1 m layer, also known as 'crop root zone'. To lessen the negative impact, farmers try to adapt to drought by following various water and soil management actions [61]. Various SSM practices, specifically mulching, legume cultivation, residue mixture, use of manure and/or compost and top soil tillage or minimal tillage are practiced as adaptation practices in drought-vulnerable area, which enhance the water retention capacity and the organic matter of the soil [2,61]. In the face of changing climate, a wise farmer may adopt several practices and technologies, which provide visible outcomes to limit their farming loss [52]. Compared to moist soil, soil organic matter and micronutrient content is likely to be low in dry soils in drought-prone areas, which is likely to be a stimulus for the farmers in such areas to practice 'use of organic fertilizer'. In dry soils, planting is difficult and hence farmers are more likely to rotate the soils to have the relatively softer parts move upward, and thus have more organic matter. Ultimately, the farmers in the drought-prone areas are less likely to practice 'zero-tillage' than their counterparts living in less water-stressed areas. Similarly, as incorporating paddy residue in dry soils is difficult despite the potential for enriching the organic components of the soil, farmers in drought-prone areas are less likely to practice 'incorporate paddy residue'.

During the dry winter seasons in saline-prone areas, it is difficult for famers to access enough fresh water for irrigation, particularly required for paddy cultivation. Hence, a likely alternative here is cultivating legumes, which are salinity-tolerant and for some of these crops do not require any land preparation by the farmers. This can explain the positive coefficients associated with the salinity vulnerability variables in the equations for 'legume cultivation' and 'zero-tillage'. Livestock rearing in salinity- stressed areas is difficult particularly due to the limited availability of grazing fields and fresh water, and the decreased availability of livestock waste reduces a household's probability of adopting 'use of organic fertilizer'.

In areas with high flood-depth, it is, indeed, difficult to practice 'use of organic fertilizer' because of the high moisture content of the soil [85]. Applying manure and composts is not possible when there is standing water in the field. Furthermore, the difficulties and challenges associated with making pits for dumping household and livestock waste is likely to be higher in areas with a high flood level. All of these considerations are likely to explain the negative coefficient associated with the variable 'flood depth' in the equation for 'use of organic fertilizer'.

Storms and cyclones have severe impact on agriculture, especially on paddy production in coastal areas [86]. Events such as storms and cyclones are often sudden and pre-season forecasts are not available, which discourages the paddy farmers from investing in SSM practices such as 'use of organic manure' and 'incorporate paddy residue'. This kind of uncertain disaster has a short time span but rapid onset effect; therefore is recognized as one of the most devastating natural disasters in Bangladesh [86]. Since 'legume cultivation' requires less investment in terms of input quantities, cost and effort compared to paddy, farmers in storm- and cyclone-vulnerable areas are more likely to prefer these crops over cereals and others that require more investment. Meanwhile, farm households living in drought-vulnerable areas have more probability to adopt SSM than others who live in areas that are not vulnerable to drought.

5. Conclusions

Maintaining soil health is crucial for sustainable agriculture production along with reducing poverty and hunger. However, the soaring rate of soil degradation is a matter of concern in contemporary times. Sustainable soil management can be an effective solution to preserve the soil quality along with ensuring sustainable food production, though farm level adoption has not yet reached its full potential. This paper aims to reveal the determinants of SSM practice adoption decisions of paddy farmers in Bangladesh using the nationally representative BIHS 2018-19 dataset. The mvprobit model was applied to recognize the determinants of the identified SSM practices and the synergies that exist between any two practices.

Four SSM practices were identified and the 'use of organic fertilizer' was the most commonly adopted (28.38%). The other three practices, viz. 'incorporate paddy residue', 'legume cultivation' and 'zero-tillage', were sporadically practiced by the farmers. Based on the insights for action theory, we argue that although all of the farmers were facing soil quality degradation as a stimulus, the difference in the adoption rate can be explained through differences in the means and conditions, which this study attempted to identify through the mvprobit model. The model revealed that climatic factors, such as flood depth, drought vulnerability, salinity vulnerability and storm and cyclone vulnerability, are critical in shaping the farmers' decisions. The direction of decision is different across the adaptation practices. In general, educated farmers and farmers with access to information and extension services had higher adoption probability. Improved infrastructure and being within economically vulnerable areas like FtF also influenced a farmer's adoption decision, but depending on the context, the directions of the effect varied.

The policy implications of this study are as follows: First, it is indispensable to increase the availability of soil health-related information and hands-on soil management training to farmers via extension services, particularly for poor and small farmers, and farmers who are in economically and climatically vulnerable areas. The Information and Communication Technology (ICT)-based dissemination strategy can be helpful in this regard. Second, the information dissemination strategy should be tailored based on the environmental conditions. For example, 'use of organic fertilizer' can be an effective strategy for drought-prone areas, but in other areas alternatives have to be identified so that the farmers can address the bio-physical constraints. Similarly, farmers in storm- and cyclone-vulnerable areas prefer 'legume cultivation'. Third, education is another effective strategy to boost SSM technology adoption. However, our empirical results observed a robust relationship between education and adoption, which argued for incorporating climate-focused information within the education system.

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Conflicts of Interest: The authors declare no conflict of interest.

Notes

1 More information is available at https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/NXKLZJ, accessed on 2 March 2021.

2 More information about salinity, rainfall and storm and cyclone vulnerability is available at https://www.bamis.gov.bd/risk-map/, accessed on 2 March 2021.

3 Description of drought vulnerability is available at https://www.bd.undp.org/content/bangladesh/en/home/library/crisis_prevention_and_recovery/vulnerability-to-climate-induced-drought--scenario---impacts.html, accessed on 2 March 2021.

4 In 2018, USD 1 was approximately TK 83 [87].

5 Feed the Future (FtF) in Bangladesh targets 20 Southern Delta districts that are prone to climatic vulnerabilities such as water scarcity, sea level rise, extreme shocks and changing weather patterns. The program targets agriculture-led growth with nutrition investments to develop physical and cognitive condition, enhance economic productivity and strengthen the resilience among the rural people. This program mainly targets theimprovement of the condition of people living in areas vulnerable to

extreme shocks, changing weather patterns, water scarcity and rising sea levels. More detailed descriptions are available at https://www.feedthefuture.gov/country/bangladesh/, accessed on 2 March 2021.

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