Soil & Tillage Research 240 (2024) 106066

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Determinants of organic soil fertilization methods use over time and in the face of climate vulnerability

Shaima Chowdhury Sharna [a], Tek Maraseni [a,b,*], Ando Mariot Radanielson [a,c]

[a] Institute for Life Science and Environment, University of Southern Queensland, Toowoomba, Queensland 4350, Australia
[b] Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[c] International Rice Research Institute, Sustainable Impact through Rice based systems, the Philippines

ARTICLE INFO

Keywords:
Organic fertilizer
Manure
Compost
Soil organic matter
Climate hazard
Ordered logit model

ABSTRACT

Implementation of environment-friendly soil organic matter (SOM) enhancing technologies (SOMET) is crucial for addressing soil degradation. This study aims to examine the usage status of SOMET (i.e., organic fertilizer, manure, and compost) from the dimension of long-term non-usage, dis-usage, late-usage and long-term usage and identify the drivers of these four behaviors of usage. We utilized national representative datasets of 1659 Bangladeshi rice-farmers for the periods of 2013, 2016 and 2020 with climate hazards data. Households were categorized into long-term non-user (48%) who does not practice SOMET in any of three survey years, dis-user (29%) as the households who abandon SOMET after practicing a period of time, late-user (20%) for the households who apply SOMET a few years later than their peer, long-term user (3%) as the households who practice SOMET for three survey years. Ordered logit model was used to quantify drivers of likelihood of being the four above defined categories. SOMET use has been found to be highly constrained by climate hazards. Flood depth, salinity, heavy rainfall, storm and cyclone vulnerability decrease likelihood of long-term use and late-use while increase the probability of long-term non-use and dis-use ($p \leq 0.01$). Alternatively, the likelihood of long-term non-use and dis-use are 12% and 4% lower in drought-prone areas. Increasing drought experiences increase the probability of long-term use and late-use ($p \leq 0.01$). Higher SOM level decreases long-term non-use but induces dis-use. Other major drivers of SOMET long-term use are older household head, more educated women in households, larger farm-size, and higher livestock values. Considering these factors in developing and implementing policies could be instrumental in promoting SOMET application at farm-level. Long-term use is context-specific with various climate and socio-economic factors, thus, designing policies and strategies should emphasize contextual variations to promote usage continuities.

1. Background

Approximately 60% of the world's population depends on agriculture for their livelihoods (Blankespoor et al., 2022), which is threatened by soil degradation and climate change (Sutton et al., 2013; Maraseni and Maroulis, 2008). Intensive agriculture has led to one-third of the world's soil being degraded (FAO, 2015a), with low-income countries in Africa and Asia experiencing severe agricultural land degradation (Barbier and Hochard, 2018). This degradation negatively impacts agricultural productivity, profitability, and sustainability (FAO, 2015a) while exacerbating food insecurity, poverty, and vulnerability to climate hazards (Yang et al., 2022; Maraseni et al., 2021; Barbier and Hochard, 2018).

One of the primary soil health indicators used to assess soil degradation is soil organic matter (SOM), primarily comprising soil organic carbon (SOC) (Maraseni et al., 2008). SOM plays a vital role in soil structure, retention and release of plant nutrients (e.g., nitrogen, phosphorus, and sulphur), soil water infiltration and storage, and carbon sequestration (Sedlář et al., 2023; Maraseni and Cockfield, 2011b). It is essential for maintaining soil fertility and thus supporting food production (Cotrufo and Lavallee, 2022; Gerke, 2022; Hasan et al., 2020; FAO, 2017). Unfortunately, SOM levels are declining worldwide, with an annual loss rate of 0.5%-1% (FAO, 2015b). About 79% of countries have experienced net declines in SOC (Prăvălie et al., 2021), reducing capacity of soils to provide essential ecosystem services (Lehmann et al., 2020).

* Corresponding author at: Institute for Life Science and Environment, University of Southern Queensland, Toowoomba, Queensland 4350, Australia.
E-mail address: Tek.Maraseni@usq.edu.au (T. Maraseni).

https://doi.org/10.1016/j.still.2024.106066
Received 24 July 2023; Received in revised form 7 February 2024; Accepted 25 February 2024
Available online 6 March 2024

Major sources of organic matter used in cropping systems include animal manure, farmyard wastes, domestic wastes, industrial wastes, sewage sludge, green manure, bio-slurry, compost, biochar, vermicompost, and incorporation of conventional straw into soil (Pizzanelli et al., 2023; Kumar et al., 2023; Hasan et al., 2020; Jin et al., 2020; Yang et al., 2020; Maraseni et al., 2010). Applications of these in farm have been reported to enhance SOM under diverse climatic conditions (Abrar et al., 2023; Rumpel et al., 2023; Sedlář et al., 2023; Antón Sobejano et al., 2021; Sommer et al., 2011). In this study, these practices are termed as SOM enhancing technologies (SOMET). Implementing SOMET, alongside other sustainable and conservation agricultural systems, can improve carbon-sequestration and increasing SOM stocks (Atoloye et al., 2022; Oliveira et al., 2022; Duan et al., 2021; Maraseni and Cockfield, 2011a, 2011b). These contribute to climate change mitigation and adaptation with other production co-benefits (Hou, 2023; Ansari et al., 2022; Ramos et al., 2022; Amelung et al., 2020; Chopin and Sierra, 2019; Soussana et al., 2019; Baldivieso-Freitas et al., 2018).

Numerous global, regional, and national initiatives are dedicated to soil conservation and sustainable farming. The Global Soil Partnership, established in 2012 with the mission of raising awareness of the significance of soils in the global agenda and promoting sustainable soil management (FAO, 2023). Another international initiative is the "4 per 1000, Soils for Food Security and Climate", launched during COP'21 to advocate the transition towards regenerative agriculture. This initiative emphasizes soil management to develop healthy and carbon-rich soils, with the goal of combating climate change and ending hunger by 2050 (UN, 2016). The United Nations Sustainable Development Goals (SDGs) also prioritize addressing land degradation and restoring degraded land through sustainable practices. Target 2.4 (#2: Zero hunger) focuses on improving soil quality through the implementation of sustainable and resilient farming practices. Additionally, target 15.3 (#15: Life on land) prioritizes the restoration of degraded soil and aims to achieve a land degradation-neutral world by 2030 (UN, 2015).

Despite the presence of these initiatives, the application of SOMET remains low (Sharna et al., 2022; Ngongo, 2016; Teklewold et al., 2013). Particularly, there is limited understanding of the decision-making process and drivers behind SOMET adoption and use (Sharna et al., 2023; Begho et al., 2022). At farm-level, decision for technologies adoption encompasses a wide range of interconnected social, institutional, and environmental issues (Mertz et al., 2011). Decision-making is time-variant, context-specific and complex, particularly under changing climatic conditions (Hisali et al., 2011). Existing literature on sustainable farm-practices revealed that demographic, socio-economic, infrastructural, and institutional factors can positively or negatively influence the adoption and use of sustainable farm-practices across different geographic context (Oduniyi, 2022; Kwadzo and Quayson, 2021; Mwaura et al., 2021; Teshager Abeje et al., 2019). For instance, farmers' perceptions of increasing temperature and decreasing rainfall motivate investment on sustainable land management as adaptation practices (Bewket, 2012; Lokonon and Mbaye, 2018). Tambet and Stopnitzky (2021) found that one year of high rainfall reduces soil conservation adoption, whilst multiple years of low rainfall increases their adoption. Nguru et al. (2021) concluded that rainfall influences adoption of various sustainable practices in different directions. Sharna et al. (2022) reported that flood and salinity reduce the usage likelihood of organic fertilizer, while drought increases the probability of its use. Determinants of continued use of sustainable soil and water conservation strategies have been so far reported as binary choices with household head's age, the number of farm laborers, incentives, market access, livestock, and farmland slope as driver of probability of continued use (Alemu et al., 2023). These studies have predominantly focused on the adoption of sustainable soil and land management technologies within specific agro-ecological regions and for single year or crop season.

There is a lack of comprehensive research on determinants of long-term adoption and use of sustainable SOMET. It is important to explore multidimensional adoption and use over time, as not all farmers who initially adopt a given practice will continue to use it in the long run, and some may discontinue while others may adopt at a later stage. Some studies (e.g., Sharna et al., 2023; Pannell and Claassen, 2020; Teshager Abeje et al., 2019; Deines et al., 2019; Kleinman et al., 2018 and Zeweld et al., 2018) have already noted the knowledge gap regarding the adoption and use of technologies over time. Particularly, the global systematic literature review (Sharna et al., 2023) and policy studies (Pannell and Claassen, 2020) confirmed the research gap on determinants of long-term use of sustainable practices among the global literature. Furthermore, the adoption of technologies highly varies across different locations (Zeweld et al., 2018). Spatial variability of the adoption and use of SOMET should be understood considering wider geographical area encompassing diverse agro-ecological conditions and climates. The impact of climate hazard vulnerability on adoption and long-term usage decisions also remains unexplored.

Considering the aforementioned context, the aim of this study is to examine the multidimensional nature of SOMET use over time, considering the challenges posed by increasingly risky climate conditions. The specific objectives of this study are as follows: 1) to assess the SOMET usage status in four types (i.e. long-term non-usage, dis-usage, late-usage and long-term usage) over the study periods of 2013, 2016 and 2020; 2) to evaluate the difference among these groups in terms of demographic, socio-economic, farm and institutional factors as well as climate hazards vulnerability (i.e. flood, drought, salinity, heavy rainfall, river erosion, storm, cyclone); and 3) to identify the drivers and constraints of long-term non-usage, dis-usage, late-usage and long-term usage of SOMET using large-data sets covering wide geographical area. Through analysing these objectives, this study will cover the global research gap on long-term use and non-use of SOMET while considering wide geographical area and various climate hazards factors.

Bangladesh was selected as case study in this research. The country's economy is hugely dependent on agriculture, contributing 11.50% of GDP (MoF, 2023). The quantity of arable land has decreased from 65.05% in 2010 to 58.19% in 2020 due to land use shifts with an annual rate of 0.68% (SRDI, 2020). Bangladesh has been experiencing severe soil degradation (SRDI, 2020). SOM depletion poses a major constraint for higher crop production in the country (Hasan et al., 2020), with approximately 35% and 60% of land having low to very low (SOM$\leq$1.7) and medium SOM level (1.71$<$SOM$<$3.4), respectively in 2020. Only 4.58% and 1.40% of lands are respectively under high (3.41$<$SOM$<$5.5) and very high level of SOM (SOM$>$5.5). Moreover, 27% of arable areas are prone to soil nutrients depletion due to intensive farming (SRDI, 2020). Bangladesh ranks as the 7th most vulnerable country to climate change according to the Global Climate Risk Index-2021 (Eckstein et al., 2021), which could result in a 33% yield loss by the next century (Karim et al., 2012). Rice is one of the most intensively grown crops in the country and the crop provides the main staple food of Bangladeshi population occupying 75% of the total cropped area (BRRI, 2020).

2. Methodology

2.1. Data collection and refinement

Data from three rounds of Bangladesh Integrated Household Survey (BIHS) conducted by the International Food Policy Research Institute (IFPRI) in 2013, 2016 and 2020 was used for this study along with climate information from government websites of Bangladesh (SRDI, 2021; DAE, 2020; MoDMR, 2016). The BIHS data of 2013, 2016 and 2020 are national surveys covering statistically representative sites of the whole Bangladesh (IFPRI, 2020; 2013). These surveys include 1) detailed data on household members' anthropometric measurements, demographic, socio-economic condition, dietary intake as well as data on plot-level agricultural production and practices and women's empowerment; 2) a community survey supplementing the BIHS data to provide information on area-specific contextual factors such as institutional and infrastructural facilities.

“Insert Fig. 1 here”

2.1.1. Dependent variables

To formulate the dependent variables of SOMET use status, a panel dataset was constructed from the survey data (BIHS 2013, 2016 and 2020). BIHS-2013, 2016 and 2020 respectively collected data from 6500, 6500 and 5604 rural households (IFPRI, 2013, 2016, 2020). As the present study is based on rice-farmers, all datasets were refined to constitute datasets of [only] rice-cultivating households. After exclusion of household who didn’t cultivate rice, 2988, 3082 and 2681 rice-cultivating households from BIHS-2013, 2016 and 2020, respectively, were retained for the study. To find the SOMET usage status of the same households in the three rounds of datasets, a next filtering was conducted by matching the households’ id from three datasets. In total, 1659 rice-farming households were matched from all three rounds of surveys. Dataset of these matched 1659 households is referred as “Matched sample”.

Use of organic fertilizer, manure and compost are the only SOMET consistently reported with the available information in all the three BIHS. A screening of the matched samples confirmed that these SOMET practices are known and used by farmers. The number of user and non-user of these SOMET were then calculated for each survey year. Here, user refers to households who used any one of the mentioned SOMET or a combination of these during rice-cultivation and non-user means those that did not. Since SOMET is an old technology in Bangladesh, the term “use” is used instead of “adoption”. Yearly-user status means the number of users and non-users within matched sample in each survey year (Fig. 2). To identify the SOMET use status over time, we categorized the below dependent variables based on SOMET application over time:

- Long-term user: that practiced SOMET continuously over all three survey years.
- Late-user: that did not use SOMET in early survey years but applied later (i.e., did not use in BIHS-2013 but applied in BIHS-2016 and BIHS-2020/did not use in BIHS-2013 and BIHS-2016 but used in BIHS-2020).
- Dis-user: that applied SOMET in early years but did not use later (i.e., used in BIHS-2013 and abandoned in both BIHS-2016 and BIHS-2020/used in BIHS-2013 and BIHS-2016, and abandoned in BIHS-2020/didn’t use in BIHS-2013 but applied in BIHS-2016 and again abandoned in BIHS-2020).
- Long-term non-user: that did not use SOMET in any of the three survey years.

This study considers only three years of BIHS datasets to define long-term user and non-user of SOMET due to the unavailability of any other relevant long-term panel datasets. This shortcoming can be fulfilled in the future research with utilizing continuous year of panel datasets with longer time-period.

2.1.2. Explanatory variables

For selecting the explanatory variables, we thoroughly reviewed the broadest set of relevant existing literature selected from Scopus, Web of Science, Science Direct and Google Scholar with the search string of ("adoption") AND (“determinants” OR “drivers”) AND (“Soil Organic Carbon” OR “Soil Organic Matter” OR "soil management" OR "soil conservation practices" OR “land management”) AND (“farming” OR “agriculture”) in the title-abstract-keywords. Different factors were identified to significantly influence sustainable farm-practices adoption and application either positively or negatively in different contexts (Alemu et al., 2023; Fentahun et al., 2023; Anik et al., 2022; Begho et al., 2022; Chuma et al., 2022; Singana Tapia and Satama Bermeo, 2022; Yifru and Miheretu, 2022; Bekele et al., 2021; Kwadzo and Quayson, 2021; Mponela et al., 2021; Mwaura et al., 2021; Oyetunde-Usman et al., 2021; Zeweld et al., 2018; Recha et al., 2015). These factors are demographic and socio-economic characteristics (e.g., age and gender of household head, dependency-ratio, household size, education, asset, income, off-farm income, women-empowerment, food insecurity status), farm characteristics (e.g., farm-size, livestock, irrigation facilities, tenure, production shock), cognitive factors (perception of soil erosion, soil degradation and climate change), institutional and infrastructural access (e.g., market distance, road access, extension service, training, risk attitude, group membership, credit access). A few literature considered the impact of biophysical factors (e.g., drought, soil fertility, slope, temperature change, average rainfall, flood, salinity, cyclone) (Fentahun et al., 2023; Anik et al., 2022; Mairura et al., 2022; Singana Tapia and Satama Bermeo, 2022).

The relevance of these variables was discussed with soil experts and production economics experts from Bangladesh and Australia and those that were consistently available from the survey data were identified to obtain a final list of variables for analyses. The list includes the households’ demographic, socio-economic and farm characteristics, institutional and infrastructural access (e.g., age and gender of household head, who makes decision regarding fertilizer application, dependency-ratio, household size, household heads’ and female members’ education, asset, off-farm income, economic shock, farm-size, livestock value, irrigation facilities, tenure, distance to nearest town, road access, subsidy card, extension service, NGO assistance, training, credit access). Some biophysical factors (e.g., flood depth, river erosion) were only available in the BIHS-2020 (IFPRI, 2020) and for an exhaustive evaluation, information on vulnerability to other climate hazards (e.g., salinity, storm, cyclone and heavy rainfall) was organized from the Bangladesh Agro-Meteorological Information Portal (DAE, 2020). Drought severity information was collected from the Ministry of Disaster Management and Relief (MoDMR, 2016).[1] Furthermore, SOM status was collected from the Soil Resource Development Institute (SRDI) (SRDI, 2021). Information from the Bangladesh Agro-Meteorological Information Portal, Ministry of Disaster Management and Relief, and Soil Resource Development Institute are collected at sub-district level. All these datasets were collated with BIHS dataset by households’ sub-district information using STATA 16 (StataCorp, 2023). Multicollinearity among these variables was tested using variance inflation factor (VIF). VIF reflects multicollinearity through quantifying the extent to which the behavior (variance) of an independent variable is influenced by its correlation with other independent variables (McCormick and Salcedo, 2017). VIF values range from 1 to infinity. VIF=1 reflects an assumed total absence of collinearity, VIF$\geq$ 2.5 indicates existence of considerable collinearity among variables, VIF$>$ 5 reflects a cause for concern and VIF$>$ 10 indicates a serious collinearity problem (Johnston et al., 2018; Thompson et al., 2017; Gareth et al., 2013). Variables with VIF more than 5 were then excluded for avoiding multicollinearity (McCormick and Salcedo, 2017). For the remaining variables, the mean VIF was 1.25. All retained variables` VIF range from 1.06 to 1.80 which minimizes to almost no correlation between the explanatory variables (Table A1). Table 1 presents the description and sources of all the considered explanatory variables.

2.2. Econometric analyses

Since the dependent variables are ordinal, an ordered logit model was used to find out the determining influencing factors of different use status and their magnitude of impact. Using latent variable, the model can be expressed as follows:

[1] Due to unavailability of current information, we utilized the drought severity information published in 2016. Drought is a recurrent event and sometimes an inherent condition, thus it might not drastically change within a few years.

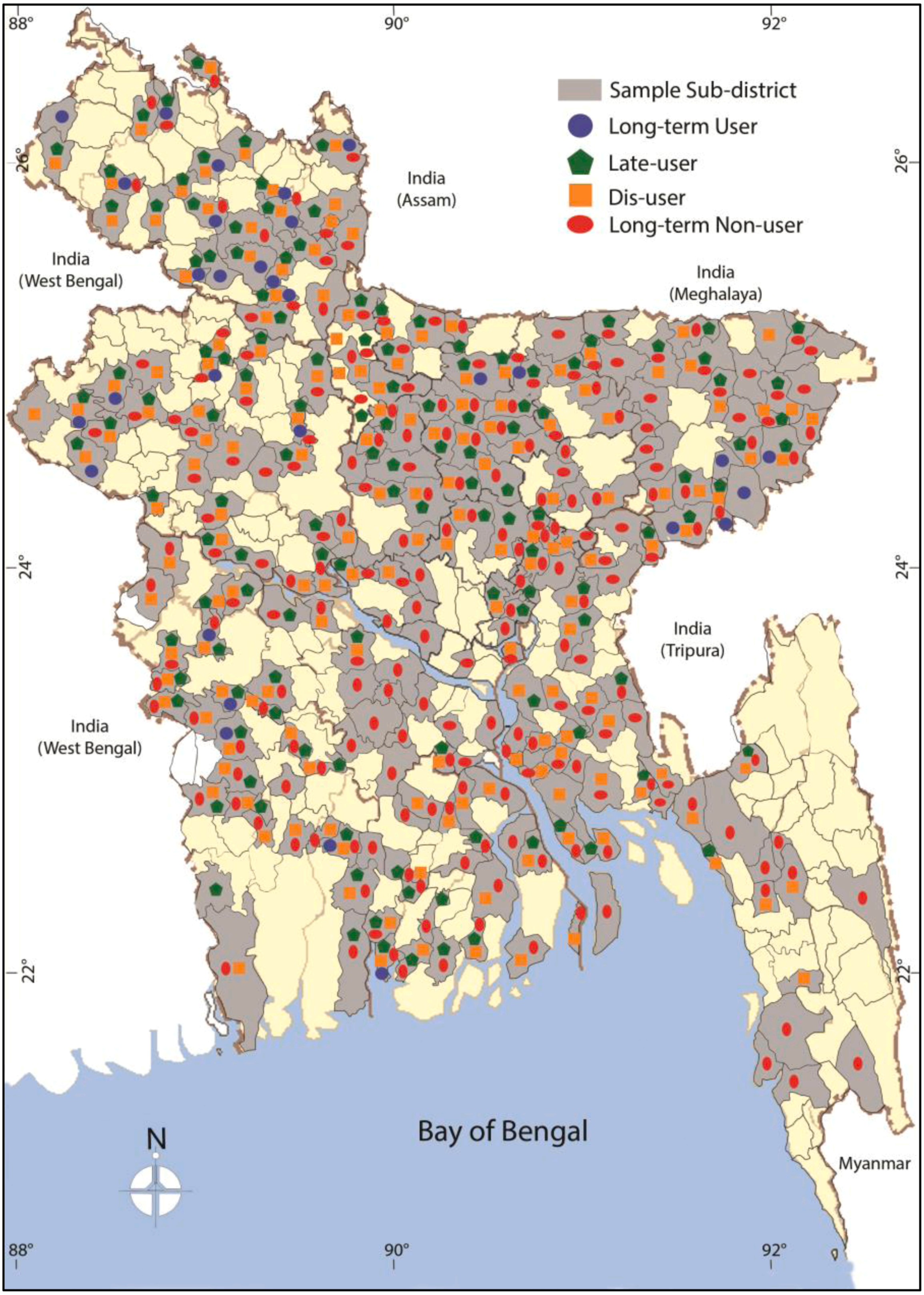

Fig. 1. Spatial distributions of matched sample location (i.e., Sub-district) in the Bangladesh Integrative Household Surveys (BIHS in 2013, 2016 and 2020) (Data source: IFPRI, 2013; IFPRI, 2016; IFPRI, 2020). The four different colored shapes represent the distribution of sub-district where the four groups belong.

$$\lambda_i^*(SOMET \quad use^*) = \sum_{i=1}^{n} X_i\beta + \varepsilon_i$$

Where *SOMET use** reflects the usage status which takes on values 0 to k-categories. The dependent variable is categorized into "four-point scale" ranges from zero to three according to the SOMET usage status:$\lambda_0 = 0 if \quad \lambda_i^* < \emptyset_0,$ *refers to* Long-term non-user $\lambda_1 = 1 if \quad \lambda_i^* < \emptyset_1,$ *refers to* Dis-user$\lambda_2 = 2 if \quad \lambda_i^* < \emptyset_2,$ *refers to* Late-user $\lambda_3 =$

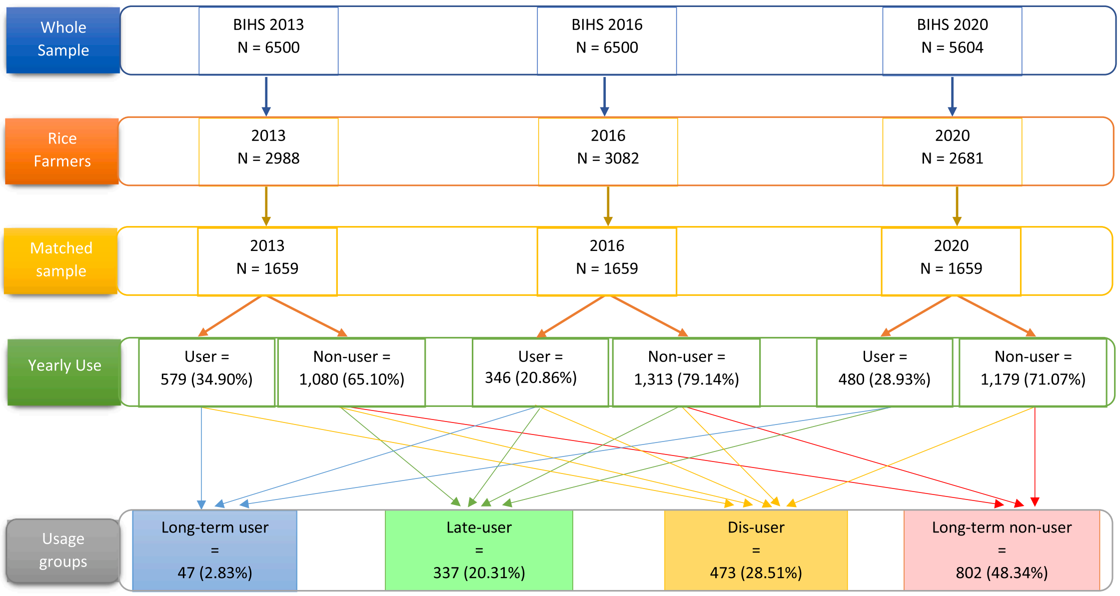

Fig. 2. Detail steps of dependent variables organization from three rounds of the Bangladesh Integrated Household Survey (BIHS 2013, 2016 and 2020).

3*if* $\lambda_i^* < \emptyset_3$, *refers to* Long-term userhere, λ_i^* is the latent variable (or unobserved) usage status, X is a vector of influential variables affecting the usage status. β is a vector of parameters denoting the relationship between use status and explanatory variables X and ε is an identically distributed error term with variance one and mean zero. j is the observed variable and γ is the threshold parameter. The threshold parameters $\emptyset_j$ are the cut-off points between adjacent values of the observed dependent variable. The probability associated with a farmers' SOMET use status can be written as follows:

$$\pi\left(\lambda_i \le \frac{j}{X_i}\right) = \Delta\left(\gamma_j - X_i^{'}\beta\right) - \Delta\left(\gamma_{j-1} - X_i^{'}\beta\right);$$

here, j is the observed variable and γ is the threshold parameter. The formal ordered logistic regression model is:

$$Logit(Y_i) = Log_e\left(\frac{\pi}{1-\pi}\right) = \beta_0 + \beta_i X_i + \varepsilon$$

here, Y_i is the dependent variable reflecting rice farmers' SOMET use status and X_i represents the determining explanatory factors (Williams, 2018). The data analyses of the ordered logit model were carried out utilizing STATA 16 to identify the determinants of long-term usage, late-usage, dis-usage, and long-term non-adoption (Williams, 2006). Descriptive statistical analyses using ANOVA and Chi-square test were respectively performed for continuous and categorical variables (Hamilton, 2012). These analyses were also conducted in STATA 16 to assess statistically significant differences among the groups (StataCorp, 2023).

3. Results

3.1. SOMET use status over time

The long-term non-user who never adopted SOMET throughout three survey years stands out among the four groups, comprising around half of the sample (48%). Following them are the dis-users (29%), who discontinued practicing SOMET after initially adopting it. The smallest proportion of sample (3%) represents long-term users, meaning they consistently practiced SOMET in each of the three survey years. Late-user constitutes 20% of the sample.

3.2. Differences for descriptive characteristics among the four groups

Differences in biophysical conditions for production and socio-economic descriptor were observed among long-term non-users, dis-users, late-users, and long-term users. These differences were significant for flood depth, drought, salinity, storm and cyclone vulnerability ($p \le 0.01$). Long-term non-users experienced an average flood depth of four feet at their farm plots, while the other three groups report that flood depth values ranging from 2.60 to 2.70 feet. Overall, a higher percentage of long-term non-users and dis-users live in salinity, storm and cyclone risk-areas compared to late-users and long-term users. Larger percentage of long-term users and late-users live in drought-prone regions compared to long-term non-users and dis-users. Vulnerability to heavy rainfall also showed significant differences among the four groups ($p \le 0.1$). More than 90% of farmers in all four groups live in heavy rainfall-risk regions. Long-term user and late-user households had more educated female members ($p \le 0.01$). Long-term user significantly owned 26%, 74% and 72% more assets, farm-size, and livestock values than the long-term non-user ($p \le 0.01$) (Table 2).

3.3. Determinants of SOMET usage over time

Table 3 illustrates the coefficients from ordered logistic regression model while Table 4 delineates the marginal effects of explanatory variables on the four SOMET usage groups. The log likelihood-ratio test is highly significant, indicating a good fit, and the pseudo-R-Square that demonstrates the model's explanatory power. The threshold estimates $\emptyset_j$ in Table 3 imply the cut-off values between any two adjacent groups of dependent variables. These are equivalent to the intercept of the linear model predicting an adoption status value if all explanatory variables are set to zero (Williams, 2018). For instance, the cut-off value 3.3 is the estimated threshold-point on the latent variable that distinguishes between 'late-user' and 'long-term user' when all the predictor variables values are set to zero.

The strongest predictors of SOMET use over time are flood depth, heavy rainfall, salinity, storm and cyclone vulnerability, drought, SOM level, age of household head, women education, farm-size, and livestock values. Experiencing heavy rainfall increases the probability of being long-term non-user and dis-user of SOMET by 22% and 8% respectively while reduces the probability of being long-term user by 2%. Salinity, storm and cyclone vulnerability increase the likelihood of being long-

Table 1
Description and summary statistics of explanatory variables for the whole matched sample (N = 1659). Means are reported with standard deviations while mean refers to the average, calculated through dividing the sum of all values by N for specific explanatory variable. Frequency describes the number and percentage among total N under a particular category.

Variable	Description	Mean (SD±)	Frequency		Source
			n	%	
Household head's education	Formal schooling completed by the household head (years)	3.55 ± 4.16			IFPRI, (2020)
Women education	Formal schooling completed by the woman, mostly household head's spouse (years)	3.31 ± 3.51			
Age	Age of the household head (years)	49.15 ± 12.18			
Dependency-ratio	Ratio of economically inactive household members to total household members (ratio)	0.74 ± 0.13			
Asset	Market value of all agricultural and non-agricultural productive assets (excluding land) owned by the household ('00USD/ per capita)	2.98 ± 2.86			
Decision	Category; Who make the decision regarding whether to use fertilizer for field.				
	Self = 1		1620	97.65	
	Spouse = 2		20	1.21	
	Other household member = 3		12	0.72	
	Other non-household member = 4		7	0.42	
Subsidy card	Dummy; households' access to agricultural input subsidy card				
	Had =1		354	21.34	
	Otherwise = 0		1305	78.66	
Extension	Dummy; households' status of receiving soil and/or fertilizer-related extension service from government/NGOs officials				
	Received = 1		327	19.71	
	Otherwise = 0		1332	80.29	
Farm size	Total area planted under different crops (ha)	0.56 ± 0.56			
Distance to town	Distance to the nearest town from the household (km)	11.13 ± 28.45			
Livestock	The market value of owned livestock by the households ('00USD)	5.75 ± 6.62			
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)	3.29 ± 3.54			
Riverbank erosion	Dummy; households' status of losing any land due to riverbank erosion				
	Lost land = 1		18	1.08	
	Otherwise = 0		1641	98.92	
Drought	Dummy; whether household live in drought-prone region				MoDMR, (2016)
	Prone-region = 1		712	42.92	
	Otherwise = 0		947	57.08	
Salinity	Dummy; whether household live in salinity affected area				DAE, (2020)
	Affected		398	23.99	
	Non-affected		1261	76.01	
Storm & cyclone	Dummy; whether household live in storm and cyclone risk area				
	Risk region = 1		1025	61.78	
	Otherwise = 0		634	38.22	
Rainfall	Dummy; whether household live in rainfall (i.e. one-day maximum rainfall in mm) risk region, 0 otherwise				
	Risk region= 1		1571	94.70	
	Otherwise = 0		88	5.30	
SOM level	Category; soil organic matter status in households' location.				SRDI, (2021)
	Very low to low (SOM ≤ 1.7) = 1		541	32.61	
	Medium (SOM = 1.71–3.4) = 2		943	56.84	
	High (SOM = 3.41–5.5) to very high (SOM >5.5) and forest area = 3		175	10.55	

Note: Mean and Standard Deviation (SD±) are calculated for continuous variables while Frequency (n and %) are estimated for categorical variables.

term non-use by 17%. One mm increase in flood-depth at farm-plot increases the probability to be long-term non-user by 3%. Farmers living in drought-prone areas have 12% lower probability to be long-term non-user and 1% higher probability to be long-term user. SOM level is negatively related with long-term non-use, but farmers with high SOM field presented higher probability to dis-use SOMET. Demographic and socio-economic characteristics such as with increasing age of household head, higher educated female member, larger farm-size and livestock values positively influence long-term use (Table 3 and Table 4).

4. Discussion

4.1. Long-term use and dis-use of SOMET

Farmer's decision-making process for technology adoption and following a practice for long-term are complex and multistage (Ng, 2020; Teshome et al., 2016). In this study, most of the farmers are long-term non-user (48%) while 29% discontinued previously adopted practices and the least are long-term user (3%) among the sample of Bangladeshi rice farmers. These findings are consistent with established reports of low adoption and use of SOMET in agricultural systems (Sharna et al., 2023; Ngongo, 2016; Teklewold et al., 2013). Fertilizers receive high priority from the Bangladesh government as a significant input for rice production and subsidies on chemical fertilizers have been supported with an overall objective of boosting agricultural production (Nasrin et al., 2018). The government provides high amount of subsidy

Table 2
Descriptive statistics of explanatory variables for four groups of soil organic matter enhancing technologies (SOMET) including long-term non-user, dis-user, late-user, long-term user. Mean refers to the average calculated through dividing the sum of all values by N for specific explanatory variable. Frequency with number and percentage among total N under a particular category are also shown. F and Chi-square value were reported with star marks representing statistical significance level for differences among the four groups.

Variables	Long-term non-user			Dis-user			Late-user			Long-term user			F/Chi-square†
	Mean	Frequency		Mean	Frequency		Mean	Frequency		Mean	Frequency		
		N	%		n	%		n	%		n	%	
Household head's education	3.58			3.37			3.59			4.42			1.00
Women education	3.25			3.21			3.39			4.55			2.21*
Age	48.67			49.21			50.13			49.72			1.19
Dependency-ratio	0.75			0.74			0.73			0.71			2.40*
Asset	2.81			2.89			3.45			3.54			4.73***
Decision													5.88
Self		776	96.76		466	98.52		331	98.22		47	100.00	
Spouse		15	1.87		3	0.63		2	0.59		0	0.00	
Other household members		7	0.87		3	0.63		2	0.59		0	0.00	
Other non-household members		4	0.50		1	0.21			0.59		0	0.00	
Subsidy card													9.57**
Had		166	20.70		86	18.18		88	26.11		14	29.79	
Didn't have		636	79.30		387	81.82		249	73.89		33	70.21	
Extension													12.89***
Received		142	17.71		85	17.97		89	26.41		11	23.40	
Didn't received		660	82.29		388	82.03		248	73.59		36	76.60	
Farm-size	0.51			0.52			0.68			0.89			14.04***
Distance to town	10.88			12.13			10.60			9.28			0.32
Livestock	4.92			6.02			6.97			8.46			11.08***
Flood depth	3.99			2.63			2.65			2.70			20.48***
Riverbank erosion													0.80
Lost land		9	1.12		6	1.27		3	0.89		0	0.00	
Didn't lose land		793	98.88		467	98.73		334	99.11		47	100.00	
Drought													55.79***
Prone region		283	35.29		210	44.40		185	54.90		34	72.34	
Non-prone region		519	64.71		263	55.60		152	45.10		13	27.66	
Salinity													38.52***
Affected		239	29.80		104	21.99		53	15.73		2	4.26	
Non-affected		563	70.20		369	78.01		284	84.27		45	95.74	
Storm & cyclone													95.84***
Risk region		573	71.45		291	61.52		142	42.14		19	40.43	
Non-risk region		229	28.55		182	38.48		195	57.86		28	59.57	
Rainfall													7.38*
Risk region		770	96.01		442	93.45		313	92.88		46	97.87	
Non-risk region		32	3.99		31	6.55		24	4.45		1	2.13	
SOM level													5.50
Very low to low		273	34.04		141	29.81		111	32.94		16	34.04	
Medium		463	57.73		275	58.14		184	54.60		21	44.68	
High to very high		66	8.23		57	12.05		42	12.46		10	21.28	
N	802			473			337			47			

Note: Mean is calculated for continuous variables while frequency (n and %) is estimated for categorical variables. † F and Chi-square value were derived from ANOVA and Pearson Chi-square test, respectively. *, ** and *** refer to significance level of 10% ($p \leq 0.1$), 5% ($p \leq 0.05$) and 1% ($p \leq 0.01$).

on chemical fertilizer which has been increasing every year (Salam et al., 2021; Nasrin et al., 2019). Heavy subsidies on chemical fertilizer have been reported associated to its inefficient application and overuse (Islam and Beg, 2021) and negatively affect continued practice of soil conservation methods (Alemu et al., 2023). Furthermore, the availability of organic fertilizer and manure has not been kept up with fertilizer demand (Hossain, 2012) due to limited number of authorized commercial composting industries (Matter et al., 2015). All of these have led to high long-term non-usage and dis-usage along with extremely low long-term use of SOMET. Policies should focus on spreading knowledge on long-run benefits of SOMET and prioritize on context-specific strategies, so that farmers can experience production and economic benefits from SOMET application along with other suitable technologies, which can ultimately improve both initial adoption and continuation of SOMET application.

4.2. Differences among the four groups based on climate and socio-economic factors

Long-term non-users live in more flood, salinity, storm and cyclone vulnerable areas in comparison to long-term user, late-user and dis-user of SOMET (Table 2). This implies that farmers in those climate hazards vulnerable areas do not use SOMET in the long-run and might prefer other technologies to adapt with these climate vulnerabilities. Existing literature also confirm low application of sustainable fertilization methods in climate vulnerable areas (Anik et al., 2022; Sharna et al., 2022, 2020). Long-term users of SOMET are in better position compared to long-term non-user, dis-user and late-user in terms of socio-economic factors, including education of female household member, owned assets, farm-size, and livestock values. The results revealed that female member of long-term user households has on average 40% more education than female member of long-term non-user household based on formal year of schooling (Table 2). Previous literature confirmed the higher education status among the members of households who use sustainable technologies (Yifru and Miheretu, 2022). The long-term user households owned 75% larger farm-size than long-term non-user and dis-user households. The adopters of sustainable land management also own more farming land than non-adopters (Yifru and Miheretu, 2022; Van Song et al., 2020). This implies that farmers who adopt and practice sustainable technologies have larger landholdings. As indicated in

Table 3
Determinants of soil organic matter enhancing technologies (SOMET) use among the four groups (i.e., long-term non-user, dis-user, late-user, and long-term user). Results were estimated from the matched sample by conducting ordinal logistic regression model in STATA 16.00.

Variables	Co-efficient	St. Er.	P-value
Household head's education	-0.01	0.01	0.68
Women education	0.03*	0.01	0.09
Age	0.01***	0.00	0.00
Dependency-ratio	-0.39	0.38	0.31
Asset	-0.03	0.02	0.22
Decision	-0.27	0.19	0.16
Subsidy card	0.07	0.12	0.58
Extension	0.09	0.12	0.46
Farm size	0.23**	0.09	0.01
Distance to town	-0.00	0.00	0.83
Livestock	0.04***	0.01	0.00
Flood depth	-0.12***	0.02	0.00
Riverbank erosion	0.14	0.49	0.76
Drought	0.46***	0.10	0.00
Salinity	-0.66***	0.14	0.00
Storm & cyclone	-0.69***	0.12	0.00
Rainfall	-0.88***	0.22	0.00
SOM level	0.13*	0.08	0.09
Threshold values			
Threshold 1 ($\varnothing_1$)	-0.59	0.43	
Threshold 2 ($\varnothing_2$)	0.84	0.43	
Threshold 3 ($\varnothing_3$)	3.31	0.45	
Model Diagnostic			
Log likelihood	-1747.55		
LR chi2(18)	267.17		
Prob > chi2	0.00		
Pseudo R2	0.34		
Number of obs.	1659		

Note: *, ** and *** refer to significance level of 10% (p≤0.1), 5% (p≤0.05) and 1% (p≤0.01).

Table 4
Marginal effect estimates for explanatory variables on four groups of soil organic matter enhancing technologies (SOMET) including long-term non-user, dis-user, late-user, long-term user. Marginal effect values are estimated from the coefficient results of the ordinal logistic regression model in STATA 16.00.

Variable	Long-term non-user	Dis-user	Late-user	Long-term user
Household head's education	0.001	-0.0004	-0.001	-0.0001
Women education	-0.01*	-0.002*	0.003*	0.006*
Age	-0.003***	0.001***	0.001***	0.0003***
Dependency-ratio	0.10	-0.03	-0.06	-0.01
Asset	0.01	-0.002	-0.004	-0.001
Decision	0.07	-0.02	-0.04	-0.01
Subsidy card	-0.02	0.01	0.01	0.001
Extension	-0.02	0.01	0.01	0.002
Farm size	-0.06**	-0.02**	0.03**	0.01**
Distance to town	0.0001	-0.00003	-0.00004	-6.36e-06
Livestock	-0.01***	0.003***	0.01***	0.001***
Flood depth	0.03***	0.01***	-0.02***	-0.003***
Riverbank erosion	-0.04	0.01	0.02	0.003
Drought	-0.12***	-0.04***	0.07***	0.01***
Salinity	0.17***	0.06***	-0.10***	-0.01***
Storm & cyclone	0.17***	0.07***	-0.11***	-0.01***
Rainfall	0.22***	0.08***	-0.13***	-0.02***
SOM level	-0.03*	0.01*	0.02	0.003

Note: *, ** and *** refer to significance level of 10% (p≤0.1), 5% (p≤0.05) and 1% (p≤0.01).

Table 2, long-term users hold two times value of livestock as of long-term non-users. This result suggests that owning more livestock increases SOMET use since the practice includes manure application which source is livestock waste (Sharna et al., 2022; Mugwe et al., 2009). Adopters of soil and water conservation practices also had higher livestock ownership than non-adopters (Yifru and Miheretu, 2022; Bekele et al., 2021).

4.3. Climate hazards and SOMET use

Climate hazards, namely, flood, drought, salinity, heavy rainfall, storm and cyclone affect different SOMET usage groups in different directions in our study. Both increase in flood-depth in the farm-plot and being in the heavy rainfall vulnerable region support long-term non-usage and dis-usage. Rising flood depth and heavy rainfall vulnerability hinder the likelihood of long-term use and late-use and support long-term non-use and dis-use (Tables 3 and 4). SOMET application and homestead composting are difficult and unfeasible during heavy rainfall and in flooded areas. The beneficial effect of SOMET on grain yield is significantly low in flooded rice field (Yang et al., 2004). Additionally, rain also washes away of applied organic fertilizer, compost and manure as those are applied on top of soil (Hagedorn et al., 1997). These factors are likely to explain the high probability for long-term non-usage and dis-usage of SOMET in flood affected and heavy rainfall vulnerable regions. Tambet and Stopnitzky (2021) reported similar results that one year of high rainfall reduces soil conservation adoption while fertilizer use is less sensitive to weather fluctuations. Nguru et al. (2021) concluded that rainfall negatively influences use of manure and Sharna et al. (2022) reported that flood reduces the likelihood of organic fertilizer use. Rain and flood forecasts can assist farmers plan the timing of SOMET application and minimize the risk of wastage due to floods and heavy rainfall. This, in turn, could enhance SOMET application in flood and rainfall-prone regions.

Farmers residing in saline-affected areas are as well observed more likely to be long-term non-user and dis-user due to the negative impact of salinity on rice production as well on soil quality in the long-term (Dewi et al., 2022; Sarker et al., 2022). Consequently, farmers tend to rely on inorganic fertilizer application in the short-term to ensure seasonal production, as benefits of SOMET may not be evident immediately due to its long-term improvement of the soil quality (Holatko et al., 2023; Li et al., 2023; Sedlář et al., 2023). Similar findings were encountered by Sharna et al. (2022) where salinity reduces the likelihood of organic fertilizer application. Increased storm and cyclone risks reduce the likelihood of long-term use of SOMET as well (Tables 3 and 4). Storm and cyclone have devastating impacts on agriculture, particularly on paddy production in coastal areas due to their sudden occurrence and lack of pre-season forecasts (BBS, 2016). For these reasons, farmers who adopted SOMET may abandon the technologies (i.e., dis-user) while others would continue to not apply it. In climate vulnerable areas, technologies that offer immediate production benefits and can overcome biotic and abiotic challenges (e.g., chemical input, stress-tolerant varieties) are more likely to have higher adoption rates (Anik et al., 2021; Sharna et al., 2020; Shikuku et al., 2017).

In contrast, drought increases the probability of long-term use and late-use whilst decreases the likelihood of long-term non-use and dis-use. Farmers in drought-prone areas use SOMET, as the practices can enhance soil water retention capacity (Zhou et al., 2020). Similar results were reported by Sharna et al. (2022) and Anik et al. (2022) where drought increases adoption of sustainable soil management practices. Furthermore, drought is a recurrent event and sometimes an inherent condition (MoDMR, 2016), thus beneficial SOMET effects in soil water retention motivate their continuous use as adaptation and climate resilience build up strategies. Therefore, it is important to promote site and climate vulnerability specific strategies targeting SOMET dissemination for improving farmers capability to adopt and practice sustainable management.

4.4. Soil organic matter status and SOMET use

Soil quality is the central issue of investing in sustainable soil or land management (Teshome et al., 2016). The probability of long-term non-use decreases for farmers in sites with high level of SOM, but it increases dis-usage. Farmers may perceive less need of SOMET with SOM improvement, leading to dis-usage. Dis-adoption can occur when the cost of technology offsets the short-term economic returns from adopting the technology, even if it has the potential to improve and sustain productivity. In the decision-making process, short-term economic return becomes a key parameter, often overriding environmental aspects (Kong et al., 2021). Some authors identified insufficient recognition of soil erosion risk as reasons for abandoning previously adopted sustainable land management technologies (Alemu et al., 2023, 2022). Furthermore, increase of SOM may induce retention of soil nutrients leading to decrease of fertiliser application efficiency in the short term in rice-based systems (Chivenge et al., 2020). SOM is the indicator of adjustment of nutrient management and the key for site specific nutrient management (Chivenge et al., 2021). Here, technical training can increase awareness among farmers about the long-term benefits of SOMET and not expecting immediate economic returns, which can reduce dis-usage rates.

4.5. *Effects of socio-economic and farm characteristics on SOMET use*

The results suggested that increase in women education increases the likelihood of being long-term user and late-user. Women contribute to 50–70% of the agricultural labor force in Asia and Pacific region (ILO, 2021), compared to 43% globally (FAO, 2020) while women contribution in agriculture sector of Bangladesh has been increasing (ADB, 2016). Hence, women education plays an important role in technology adoption and continued usage. Farm-households with higher education level, especially with educated female member, have higher knowledge acceptance and awareness about soil degradation (Mairura et al., 2022; Yifru and Miheretu, 2022; Betela and Wolka, 2021; Tesfahunegn, 2019), which increase likelihood of SOMET use. Similar role of women education was reported by Xu et al. (2022) and Silva et al. (2022) respectively for adoption of sustainable practice and best management practices. Therefore, initiatives that improve women access to education and information would be beneficial for SOMET application in the long-run and thus improve sustainability of Bangladeshi rice farming systems.

Farmers who report owning larger farm-size, have higher probability of being long-term user and late-user. Similar results were noted by Fentahun et al. (2023) where larger land ownership increases investment in manure and compost. Achieving economies of scale is easy in large farms due to huge production with stronger risk resistance, technology adoption capabilities, and better understanding of field management (Xu et al., 2022). Thus, they incline more to use SOMET for long-term. In contrast, small-farmers are constrained by farm-conditions including limited affordability for inputs and scope of technology application which decreases application of sustainable options (Xu et al., 2022). Another farm-characteristic is the value of owned livestock which positively contributes to SOMET use over time. Livestock waste acts as a source of organic manure which contributes to increasing likelihood of SOMET application (Sharna et al., 2022; Mugwe et al., 2009). Likewise results were found by Mairura et al. (2022). All these results recommend strengthening farm-households socio-economic condition which eventually strengthens the capacity to adopt and use sustainable management in the long-run mitigating land degradation and securing food production at regional, national and global scale.

5. Conclusion and recommendation

Sustainable farm-practices such as SOMET can sustain production without unintentional detrimental impact on environment. This study on SOMET use among Bangladeshi rice farmers found that long-term application of SOMET is low (3%) and almost 48% of the households are long-term non-user followed by dis-user (29%). We observed significant differences of environmental and socio-economic conditions among the identified SOMET user categories, namely, long-term non-user, dis-user, late-user and long-term user. The main contributing factors decreasing likelihood of long-term application of SOMET are flood depth, salinity, heavy rainfall, storm and cyclone vulnerability. In contrast, increase of drought risk, farm-size and value of owned livestock increase likelihood of long-term usage. Higher SOM level reduces the probability of long-term non-use but increases dis-use. Women education significantly raises SOMET long-term use highlighting the role of women's education and empowerment for sustainability in agriculture.

This study reaffirms findings from previous literature and provides insights for policymakers to promote adoption and use of sustainable practices. Long-term use of SOMET is context-specific and hindered by climate hazards, necessitating context-specific policies based on climate vulnerability, local pedoclimatic and environmental conditions rather than common policies for all climate vulnerable areas. Likewise, variations in the effects of socioeconomic and farm characteristics should be considered when designing adoption strategies. Enhancing knowledge and skills of farmers and female household members through technical and resource supports could assist continuation of SOMET application. Uplifting farmers' economic status through livestock ownership and larger farm size can make them more receptive to sustainable technologies, focusing on long-run profitability over short-term gains. Agricultural subsidies and rewards in both short and long-term can encourage initial adoption and continuation of application of soil organic fertilization methods.

Further comprehensive and long-run research is required with consecutive yearly data on farmers' perception and experience on short-term and long-term benefits of SOMET adoption and application. Revealing of farmer's experience on impact after SOMET application can provide thorough reasons of long-term non-usage, dis-usage and late-usage. This would assist policy makers to design suitable policies to reduce dis-use and long-term non-use. Future studies also need to pay more attention on how to promote SOMET along with other climate mitigation and adaptation strategies which can ultimately improve farmers ability to adapt to climate change.

Funding

This research did not receive any external funding.

CRediT authorship contribution statement

Shaima Chowdhury Sharna: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. **Tek Maraseni:** Conceptualization, Supervision, Writing – review & editing. **Ando Radanielson:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest in terms of both financial and personal perspective that could have influenced the work.

Data availability

All the utilized data are available online.

Acknowledgements

The first author is grateful to the University of Southern Queensland for providing "International Fees Research scholarship" and "Research and Training Program Stipend" which support her to conduct this research. Besides, the authors are grateful to IFPRI for making the dataset open access.

Annex.

Table A1
Multi-collinearity test among the explanatory variables (i.e., VIF = Variance Inflation Factor)

Variable	VIF	1/VIF
Head education	1.40	0.71
Women education	1.46	0.68
Age	1.20	0.83
Earning-ratio	1.12	0.89
Asset	1.80	0.55
Decision	1.03	0.97
Subsidy card	1.10	0.90
Extension	1.07	0.93
Area planted	1.15	0.86
Distance to town	1.06	0.95
Livestock	1.70	0.58
Flood depth	1.08	0.92
Riverbank erosion	1.06	0.94
Drought	1.14	0.87
Salinity	1.47	0.68
Storm & cyclone	1.42	0.70
Rainfall	1.14	0.88
SOMS	1.06	0.94
Mean VIF	1.25	

References

Abrar, M.M., Shah, S.A.A., Sun, N., Mehmood, K., Aziz, T., Waqas, M.A., Mustafa, A., 2023. Long-term manure application enhances organic carbon and nitrogen stocks in Mollisol subsoil. Land Degrad. Dev. 34 (3), 815–832.
ADB. (2016). Women at Work. Asian Development Bank. Women at Work | Asian Development Bank (adb.org).
Alemu, T., Tolossa, D., Senbeta, F., Zeleke, T., 2022. Factors Influencing Smallholder Farmers' Decision to Abandon Introduced Sustainable Land Management Technologies in Central Ethiopia. J. Sustain. Agric. *37* (2), 385–405.
Alemu, T., Tolossa, D., Senbeta, F., Zeleke, T., 2023. Household determinants of continued adoption of sustainable land management measures in central Ethiopia. Heliyon *9*, 3.
Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Chabbi, A., 2020. Towards a global-scale soil climate mitigation strategy. Nat. Commun. 11 (1), 5427.
Anik, A.R., Rahman, S., Sarker, J.R., Al Hasan, M., 2021. Farmers' adaptation strategies to combat climate change in drought prone areas in Bangladesh. Int. J. Disaster Risk Reduct. *65*, 102562.
Anik, A.R., Begho, T., Sharna, S.C., Eory, V., Rahman, M.M., 2022. Toward improving nitrogen use efficiency in rice production: the socio-economic, climatic and technological determinants of briquette urea adoption. Renew. Agric. Food Syst. *37* (5), 417–428.
Ansari, M.A., Choudhury, B.U., Layek, J., Das, A., Lal, R., Mishra, V.K., 2022. Green manuring and crop residue management: effect on soil organic carbon stock, aggregation, and system productivity in the foothills of Eastern Himalaya (India). Soil Tillage Res. *218*, 105318.
Antón Sobejano, R., Arricibita Videgain, J., Ruiz Sagaseta de Ilurdoz, A., Enrique Martín, A., De Soto García, I.S., Orcaray Echeverría, L., Virto Quecedo, Í., 2021. Soil organic carbon monitoring to assess agricultural climate change adaptation practices in Navarre, Spain. Reg. Environ. Change 21 (2021), 63.
Atoloye, I.A., Jacobson, A.R., Creech, J.E., Reeve, J.R., 2022. Soil organic carbon pools and soil quality indicators 3 and 24 years after a one-time compost application in organic dryland wheat systems. Soil Tillage Res. *224*, 105503.
Baldivieso-Freitas, P., Blanco-Moreno, J.M., Armengot, L., Chamorro, L., Romanyà, J., Sans, F.X., 2018. Crop yield, weed infestation and soil fertility responses to contrasted ploughing intensity and manure additions in a Mediterranean organic crop rotation. Soil Tillage Res. *180*, 10–20.
Barbier, E.B., Hochard, J.P., 2018. Land degradation and poverty. Nat. Sustain. 1 (11), 623–631.
BBS. (2016). Bangladesh Disaster-related Statistics-2015, Climate Change and Natural Disaster Perspectives. Bangladesh Bureau of Statistics (BBS), Ministry of Planning, Government of the Peoples' Republic of Bangladesh: Dhaka, Bangladesh.
Begho, T., Glenk, K., Anik, A.R., Eory, V., 2022. A systematic review of factors that influence farmers' adoption of sustainable crop farming practices: Lessons for sustainable nitrogen management in South Asia. J. Sustain. Agric. Environ. *1* (2), 149–160.
Bekele, R.D., Mirzabaev, A., Mekonnen, D., 2021. Adoption of multiple sustainable land management practices among irrigator rural farm households of Ethiopia. Land Degradation Develop. 32 (17), 5052–5068.
Betela, B., Wolka, K., 2021. Evaluating soil erosion and factors determining farmers' adoption and management of physical soil and water conservation measures in Bachire watershed, southwest Ethiopia. Environ. Chall. *5*, 100348.
Bewket, W., 2012. Climate change perceptions and adaptive responses of smallholder farmers in central highlands of Ethiopia. Int. J. Environ. Stud. *69* (3), 507–523.
Blankespoor, B., Ru, Y., Wood-Sichra, U., Thomas, T.S., You, L., & Kalvelagen, E. (2022). Estimating Local Agricultural GDP across the World.
BRRI (2020) Rice in Bangladesh. Rice knowledge bank. Bangladesh Rice Research Institute. Available at 〈http://www.knowledgebank-brri.org/riceinban.php〉 (accessed on 4th February 2023).
Chivenge, P., Rubianes, F., Van Chin, D., Van Thach, T., Khang, V.T., Romasanta, R.R., Van Trinh, M., 2020. Rice straw incorporation influences nutrient cycling and soil organic matter. Sustain. rice straw Manag. 131–144.
Chivenge, P., Sharma, S., Bunquin, M.A., Hellin, J., 2021. Improving nitrogen use efficiency—a key for sustainable rice production systems. Front. Sustain. Food Syst. *5*, 737412.
Chopin, P., Sierra, J., 2019. Reduced tillage and organic amendments can offset the negative impact of climate change on soil carbon: a regional modelling study in the Caribbean. Soil Tillage Res. *192*, 113–120.
Chuma, G.B., Mondo, J.M., Ndeko, A.B., Bagula, E.M., Lucungu, P.B., Bora, F.S., Bielders, C.L., 2022. Farmers' knowledge and Practices of Soil Conservation Techniques in Smallholder Farming Systems of Northern Kabare, East of DR Congo. Environ. Chall. *7*, 100516.
Cotrufo, M.F., Lavallee, J.M., 2022. Soil organic matter formation, persistence, and functioning: a synthesis of current understanding to inform its conservation and regeneration. Adv. Agron. *172*, 1–66.
DAE. (2020). Bangladesh Agro-Meteorological Information Portal. Department of Agricultural Extension (DAE). Available online at Bangladesh Agro-Meteorological Information System (bamis.gov.bd).
Deines, J.M., Wang, S., Lobell, D.B., 2019. Satellites reveal a small positive yield effect from conservation tillage across the US Corn Belt. Environ. Res. Lett. *14* (12), 124038.
Dewi, E.S., Abdulai, I., Bracho-Mujica, G., Rötter, R.P., 2022. Salinity constraints for small-scale agriculture and impact on adaptation in North Aceh, Indonesia. Agronomy *12* (2), 341.
Duan, Y., Yang, H., Shi, T., Zhang, W., Xu, M., Gao, S., 2021. Long-term manure application to improve soil macroaggregates and plant-available nitrogen in a Mollisol. Soil Tillage Res. *211*, 105035.
Eckstein, D., Künzel, V., & Schäfer, L. (2021). The global climate risk index 2021. Bonn: Germanwatch.
FAO. (2015a). The State of the World's Land and Water Resources for Food and Agriculture Managing Systems at Risk. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.
FAO. (2015b). Status of the World's Soil Resources (SWSR)- Main Report. Food and Agriculture Organization of United Nations (FAO), Rome, Italy.
FAO. (2017). Global soil organic carbon map. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. 〈https://www.fao.org/3/i8195e/i8195e.pdf〉.
FAO. (2020). Reduce Rural Poverty: Women in agriculture. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. Women in agriculture | Reduce Rural Poverty | Food and Agriculture Organization of the United Nations (fao.org).

FAO. (2023). Global Soil Partnership. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. Global Soil Partnership | Food and Agriculture Organization of the United Nations (fao.org).
Fentahun, G., Amsalu, T., Birhanie, Z., 2023. Farmers' perceptions about the influence of land fragmentation and land quality on sustainable land management in the upper lake Tana Basin: evidence from Dera District. Cogent Econ. Financ. *11* (1), 2160132.
Gareth, J., Daniela, W., Trevor, H., & Robert, T. (2013). An introduction to statistical learning: with applications in R. Spinger.
Gerke, J., 2022. The central role of soil organic matter in soil fertility and carbon storage. Soil Syst. *6* (2), 33.
Hagedorn, F., Steiner, K.G., Sekayange, L., Zech, W., 1997. Effect of rainfall pattern on nitrogen mineralization and leaching in a green manure experiment in South Rwanda. Plant Soil *195*, 365–375.
Hamilton, L.C. (2012). Statistics with Stata: version 12. Cengage Learning.
Hasan, M.N., Bari, M.A., Rahman, M.L., Bhander, B.K., 2020. Soil fertility trends in Bangladesh 2010 to 2020. SRSRF Proj. 38–43.
Hisali, E., Birungi, P., Buyinza, F., 2011. Adaptation to climate change in Uganda: evidence from micro level data. Glob. Environ. Change *21* (4), 1245–1261.
Holatko, J., Hammerschmiedt, T., Mustafa, A., Kintl, A., Skarpa, P., Ryant, P., Brtnicky, M., 2023. Time-dependent impact of co-matured manure with elemental sulfur and biochar on the soil agro-ecological properties and plant biomass. Sci. Rep. 13 (1), 4327.
Hossain, S.T., 2012. Organic farming in populated area: Bangladesh–an example of case study. Org. Farming Popul. Area.: Bangladesh– Ex. case Study 105–113.
Hou, D., 2023. Sustainable soil management for food security. Soil Use Manag. *39* (1), 1–7.
IFPRI. (2013). Bangladesh Integrated Household Survey (BIHS) 2011-2012. International Food Policy Research Institute (IFPRI). Accessed on 1st Jan 2023 from Bangladesh Integrated Household Survey (BIHS) 2011-2012 | IFPRI: International Food Policy Research Institute.
IFPRI. (2016). Bangladesh Integrated Household Survey (BIHS) 2015. International Food Policy Research Institute (IFPRI). Accessed on 1st Jan 2023 from Bangladesh Integrated Household Survey (BIHS) 2015 - IFPRI Dataverse (harvard.edu).
IFPRI. (2020). Bangladesh Integrated Household Survey (BIHS) 2018-2019. International Food Policy Research Institute (IFPRI). Accessed on 1st Jan 2023 from Bangladesh Integrated Household Survey (BIHS) 2018-2019 - IFPRI Dataverse (harvard.edu).
ILO. (2021). ILO monitor: COVID-19 and the world of work. Updated estimates and analysis. 7th edition. Geneva: International Labour Office.
Islam, M., Beg, S., 2021. Rule-of-thumb instructions to improve fertilizer management: Experimental evidence from Bangladesh. Econ. Dev. Cult. Change *70* (1), 237–281.
Jin, Z., Shah, T., Zhang, L., Liu, H., Peng, S., Nie, L., 2020. Effect of straw returning on soil organic carbon in rice–wheat rotation system: a review. Food Energy Secur. *9* (2), e200.
Johnston, R., Jones, K., Manley, D., 2018. Confounding and collinearity in regression analysis: a cautionary tale and an alternative procedure, illustrated by studies of British voting behaviour. Qual. Quant. *52*, 1957–1976.
Karim, M.R., Ishikawa, M., Ikeda, M., Islam, M.T., 2012. Climate change model predicts 33% rice yield decrease in 2100 in Bangladesh. Agron. Sustain. Dev. *32* (4), 821–830.
Kleinman, P.J.A., Spiegal, S., Rigby, J.R., Goslee, S.C., Baker, J.M., Bestelmeyer, B.T., Walthall, C.L., 2018. Advancing the sustainability of US agriculture through long-term research. J. Environ. Qual. 47 (6), 1412–1425.
Kong, R., Castella, J.C., Suos, V., Leng, V., Pat, S., Diepart, J.C., Tivet, F., 2021. Investigating farmers' decision-making in adoption of conservation agriculture in the Northwestern uplands of Cambodia. Land Use Policy *105*, 105404.
Kumar, N., Chaudhary, A., Ahlawat, O.P., Naorem, A., Upadhyay, G., Chhokar, R.S., Singh, G.P., 2023. Crop residue management challenges, opportunities and way forward for sustainable food-energy security in India: a review. Soil Tillage Res. *228*, 105641.
Kwadzo, M., Quayson, E., 2021. Factors influencing adoption of integrated soil fertility management technologies by smallholder farmers in Ghana. Heliyon *7* (7), e07589.
Lehmann, J., Bossio, D.A., Kögel-Knabner, I., Rillig, M.C., 2020. The concept and future prospects of soil health. Nature Reviews Earth Environ. *1* (10), 544–553.
Li, H., Zhou, Y., Mei, H., Li, J., Chen, X., Huang, Q., Tang, J., 2023. Effects of long-term application of earthworm bio-organic fertilization technology on soil quality and organo-mineral complex in tea garden. Forests 14 (2), 225.
Lokonon, B.O., Mbaye, A.A., 2018. Climate change and adoption of sustainable land management practices in the Niger basin of Benin. In. In: Natural Resources Forum, Vol. 42. Blackwell Publishing Ltd, Oxford, UK, pp. 42–53.
Mairura, F.S., Musafiri, C.M., Kiboi, M.N., Macharia, J.M.', Ng'etich, O.K., Shisanya, C. A., Ngetich, F.K., 2022. Farm factors influencing soil fertility management patterns in Upper Eastern Kenya. Environ. Chall. *6*, 100409.
Maraseni, T., An-Vo, D.A., Mushtaq, S., Reardon-Smith, K., 2021. Carbon smart agriculture: an integrated regional approach offers significant potential to increase profit and resource use efficiency, and reduce emissions. J. Clean. Prod. *282*, 124555.
Maraseni, T.N., Cockfield, G., 2011a. Crops, cows or timber? Including carbon values in land use choices. Agric. Ecosyst. Environ. *140* (1-2), 280–288.
Maraseni, T.N., Cockfield, G., 2011b. Does the adoption of zero tillage reduce greenhouse gas emissions? An assessment for the grains industry in Australia. Agric. Syst. *104*, 451–458.
Maraseni, T.N., Maroulis, J., 2008. Piggery: from environmental pollution to a climate change solution. J. Environ. Sci. Health Part B *43* (4), 358–363.
Maraseni, T.N., Mathers, N.J., Harms, B., Cockfield, G., Apan, A., Maroulis, J., 2008. Comparing and predicting soil carbon quantities under different land use systems on the Red Ferrosol soils of Southeast Queensland. J. Soil Water Conserv. *63* (4), 250–257.
Maraseni, T.N., Chen, G., Guangren, Q., 2010. Biochar: maximising the benefits. Int. J. Environ. Stud. *67* (3), 319–327.
McCormick, K., & Salcedo, J. (2017). *SPSS* statistics for data analysis and visualization. John Wiley & Sons.
Mertz, O., Mbow, C., Reenberg, A., Genesio, L., Lambin, E.F., D'haen, S., Sandholt, I., 2011. Adaptation strategies and climate vulnerability in the Sudano-Sahelian region of West Africa. Atmos. Sci. Lett. 12 (1), 104–108.
MoDMR. (2016). Vulnerability to Climate Induced Drought: Scenario and Impact; Comprehensive Disaster Management Program (CDMP II); Ministry of Disaster Management and Relief, Government of Bangladesh, Dhaka, Bangladesh. Accessed on 1st Feb 2023 from Vulnerability to Climate Induced Drought: Scenario & Impacts | United Nations Development Programme (undp.org).
MoF. (2023). Bangladesh Economic Review (BER) 2022, Department of Finance, Ministry of Finance (MoF), Government of the People's Republic of Bangladesh, Dhaka.Pp91.
Mponela, P., Villamor, G.B., Snapp, S., Tamene, L., Le, Q.B., Borgemeister, C., 2021. The role of women empowerment and labour dependency on adoption of integrated soil fertility management in Malawi. Soil Use Manag. *37* (2), 390–402.
Mugwe, J., Mugendi, D., Mucheru-Muna, M., Merckx, R., Chianu, J., Vanlauwe, B., 2009. Determinants of the decision to adopt integrated soil fertility management practices by smallholder farmers in the central highlands of Kenya. Exp. Agric. *45* (1), 61–75.
Mwaura, G.G., Kiboi, M.N., Bett, E.K., Mugwe, J.N., Muriuki, A., Nicolay, G., Ngetich, F. K., 2021. Adoption intensity of selected organic-based soil fertility management technologies in the Central Highlands of Kenya. Front. Sustain. Food Syst. *4*, 570190.
Nasrin, M., Bauer, S., Arman, M., 2018. Assessing the impact of fertilizer subsidy on farming efficiency: A case of Bangladeshi farmers. Open Agric. *3* (1), 567–577.
Nasrin, M., Bauer, S., Arman, M., 2019. Dataset on measuring perception about fertilizer subsidy policy and factors behind differential farm level fertilizer usage in Bangladesh. Data Brief. *22*, 851–858.
Ngongo, R.N. (2016). Factors influencing the adoption of modern agricultural technologies by small scale farmers: The case of Thika East Sub-County, Kenya. A Masters Project, Nairobi: University of Nairobi.
Nguru, W.M., Gachene, C.K., Onyango, C.M., Girvetz, E.H., 2021. Factors constraining the adoption of soil organic carbon enhancing technologies among small-scale farmers in Ethiopia. Heliyon *7* (12), e08497.
Oduniyi, O.S., 2022. Factors driving the adoption and use extent of sustainable land management practices in South Africa. Circ. Econ. Sustain. *2* (2), 589–608.
Oliveira, J.F., Oliveira, De, Ruiz, J.C.S., de Cesare Barbosa, D.B., Tavares, G.M., Filho, J., 2022. Changes in carbon and phosphorus storages and humic substances in a Ferralsol, after tillage and animal manures applications. Soil Tillage Res. *220*, 105358.
Oyetunde-Usman, Z., Olagunju, K.O., Ogunpaimo, O.R., 2021. Determinants of adoption of multiple sustainable agricultural practices among smallholder farmers in Nigeria. Int. Soil Water Conserv. Res. *9* (2), 241–248.
Pannell, D.J., Claassen, R., 2020. The roles of adoption and behavior change in agricultural policy. Appl. Econ. Perspect. Policy *42* (1), 31–41.
Pizzanelli, S., Calucci, L., Forte, C., Borsacchi, S., 2023. Studies of organic matter in composting, vermicomposting, and anaerobic digestion by 13C solid-State NMR spectroscopy. Appl. Sci. *13* (5), 2900.
Prăvălie, R., Nita, I.A., Patriche, C., Niculiță, M., Birsan, M.V., Roșca, B., Bandoc, G., 2021. Global changes in soil organic carbon and implications for land degradation neutrality and climate stability. Environ. Res. *201*, 111580.
Ramos, M.L.G., de Melo Pereira do Nascimento, R.S., Silva, A.M.M., Silva, S.B., de Oliveira Júnior, M.P., 2022. Carbon and nitrogen stocks in cultivation systems of a Quilombola community in the Brazilian Cerrado. Reg. Environ. Change *22* (3), 81.
Recha, C.W., Mukopi, M.N., Otieno, J.O., 2015. Socio-economic determinants of adoption of rainwater harvesting and conservation techniques in semi-arid Tharaka sub-county, Kenya. Land Degrad. Dev. *26* (7), 765–773.
Rumpel, C., Amiraslani, F., Bossio, D., Chenu, C., Cardenas, M.G., Henry, B., Varela-Ortega, C., 2023. Studies from global regions indicate promising avenues for maintaining and increasing soil organic carbon stocks: the Scientific and Technical Committee of the 4 per 1000 initiative. Reg. Environ. Change 23 (1), 8.
Salam, M.A., Sarker, M.N.I., Sharmin, S., 2021. Do organic fertilizer impact on yield and efficiency of rice farms? Empirical evidence from Bangladesh. Heliyon *7* (8), e07731.
Sarker, J.R., Rolfe, J., Ananda, J., 2022. Analysis of technical efficiency of dry season rice production in saline and non-saline areas of Bangladesh. J. Environ. Manag. *316*, 115256.
Sedlář, O., Balík, J., Černý, J., Kulhánek, M., Smatanová, M., 2023. Long-term application of organic fertilizers in relation to soil organic matter quality. Agronomy *13* (1), 175.
Sharna, S.C., Kamruzzaman, M., Anik, A.R., 2020. Determinants of improved chickpea variety adoption in high barind region of Bangladesh. Int. J. Agric. Res. Innov. Technol. *10* (1), 56–63.
Sharna, S.C., Anik, A.R., Rahman, S., Salam, M., 2022. Impact of social, institutional and environmental factors on the adoption of sustainable soil management practices: an empirical analysis from Bangladesh. Land *11* (12), 2206.
Sharna, S.C., Maraseni, T., Radanielson, A., 2023. A global systematic literature review on adoption of sustainable soil management practices (1994-2022). Soil Use Manag.
Silva, J.V., Pede, V.O., Radanielson, A.M., Kodama, W., Duarte, A., de Guia, A.H., Stuart, A.M., 2022. Revisiting yield gaps and the scope for sustainable intensification for irrigated lowland rice in Southeast Asia. Agric. Syst. *198*, 103383.
Singana Tapia, D., Satama Bermeo, M., 2022. Factors supporting the adoption of soil conservation practices: evidence from Ecuadorian smallholder farmers. Land Degrad. Dev. *33* (4), 658–669.

Sommer, R., Ryan, J., Masri, S., Singh, M., Diekmann, J., 2011. Effect of shallow tillage, moldboard plowing, straw management and compost addition on soil organic matter and nitrogen in a dryland barley/wheat-vetch rotation. Soil Tillage Res. *115*, 39–46.
Soussana, J.F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Lal, R., 2019. Matching policy and science: rationale for the '4 per 1000-soils for food security and climate'initiative. Soil Tillage Res. *188*, 3–15.
SRDI. (2021). Organic Matter Status Map Bangladesh, 2020. Soil Resource Development Institute (SRDI). Available at Soil Resource Development Institute (SRDI)-Government of the People\'s Republic of Bangladesh (portal.gov.bd).
StataCorp. (2023). Stata: Release 18. Statistical Software. College Station, TX: StataCorp LLC.
Sutton M.A., Bleeker A., Howard C.M., Bekunda M., Grizzetti B.,…, & Zhang Y. (2013) Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.
Tambet, H., Stopnitzky, Y., 2021. Climate adaptation and conservation agriculture among Peruvian farmers. Am. J. Agric. Econ. *103* (3), 900–922.
Teklewold, H., Kassie, M., Shiferaw, B., 2013. Adoption of multiple sustainable agricultural practices in rural Ethiopia. J. Agric. Econ. *64* (3), 597–623.
Tesfahunegn, G.B., 2019. Farmers' perception on land degradation in northern Ethiopia: implication for developing sustainable land management. Soc. Sci. J. *56* (2), 268–287.
Teshager Abeje, M., Tsunekawa, A., Adgo, E., Haregeweyn, N., Nigussie, Z., Ayalew, Z., Berihun, D., 2019. Exploring drivers of livelihood diversification and its effect on adoption of sustainable land management practices in the Upper Blue Nile Basin, Ethiopia. Sustainability 11 (10), 2991.
Teshome, A., de Graaff, J., Ritsema, C., Kassie, M., 2016. Farmers' perceptions about the influence of land quality, land fragmentation and tenure systems on sustainable land management in the north western Ethiopian highlands. Land degradation Develop *27* (4), 884–898.
Thompson, C.G., Kim, R.S., Aloe, A.M., Becker, B.J., 2017. Extracting the variance inflation factor and other multicollinearity diagnostics from typical regression results. Basic Appl. Soc. Psychol. *39* (2), 81–90.
UN, (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. United Nations (UN).
UN, (2016). The "4 per 1000" Initiative and its implementation. United Nations (UN). 〈https://sdgs.un.org/partnerships/4-1000-initiative-and-its-implementation〉.
Van Song, N., Cuong, H.N., Huyen, V.N., Rañola Jr, R.F., 2020. The determinants of sustainable land management adoption under risks in upland area of Vietnam. Sustain. Futures *2*, 100015.
Williams, R., 2006. Generalized ordered logit/partial proportional odds models for ordinal dependent variables. Stata J. *6* (1), 58–82.
Williams, R. (2018). Ordered logit models–basic & intermediate topics. University of Notre Dame.
Xu, Y., Liu, H., Lyu, J., Xue, Y., 2022. What Influences Farmers' Adoption of Soil Testing and Formulated Fertilization Technology in Black Soil Areas? An Empirical Analysis Based on Logistic-ISM Model. Int. J. Environ. Res. Public Health *19* (23), 15682.
Yang, A.L., Raghuram, N., Adhya, T.K., Porter, S.D., Panda, A.N., Kaushik, H., Jeffery, R., 2022. Policies to combat nitrogen pollution in South Asia: gaps and opportunities. Environ. Res. Lett. 17 (2), 025007.
Yang, C., Yang, L., Yang, Y., Ouyang, Z., 2004. Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. Agric. Water Manag. *70* (1), 67–81.
Yang, S., Chen, X., Jiang, Z., Ding, J., Sun, X., Xu, J., 2020. Effects of biochar application on soil organic carbon composition and enzyme activity in paddy soil under water-saving irrigation. Int. J. Environ. Res. Public Health *17* (1), 333.
Yifru, G.S., Miheretu, B.A., 2022. Farmers' adoption of soil and water conservation practices: the case of lege-lafto watershed, dessie zuria district, south wollo, Ethiopia. PloS One *17* (4), e0265071.
Zeweld, W., Van Huylenbroeck, G., Tesfay, G., Azadi, H., Speelman, S., 2018. Impacts of socio-psychological factors on actual adoption of sustainable land management practices in dryland and water stressed areas. Sustainability *10* (9), 2963.
Zhou, H., Chen, C., Wang, D., Arthur, E., Zhang, Z., Guo, Z., Mooney, S.J., 2020. Effect of long-term organic amendments on the full-range soil water retention characteristics of a Vertisol. Soil Tillage Res. *202*, 104663.