Climate change adaptation strategies and food productivity in Nepal: A counterfactual analysis

Abstract

It is widely accepted that climate change is having a significant effects on global agriculture. However the precise impacts depend to a large degree on the nature of adaptations which take place. But, little is known about whether adaptation practices adopted by farmers in less developed countries support farm productivity. To this end, this study first identifies the actual adaptation practices adopted by farming households. This is done by linking farmers' perception of changes in local climatic conditions, its impact on agricultural production and the adjustments they have made in response to climate change impacts. Simultaneous equation models are then employed together with the endogenous switching regression methodology to examine the factors that influence farmers' decisions to adopt different climate change adaptation strategies. How the adoption of these strategies impact food productivity is also examined. Based on a survey of 720 farming households in Nepal, our results show that adoption of adaptation strategies have significantly increased food productivity. Among the adaptation strategies, soil and water management are shown to have the largest impact on food productivity followed by adjustments to the timing of farm operations and crop and varietal adjustment. Factors influencing adoption of adaptation strategies include age and education of the household head (the decision-maker of adaptation strategies), family size, households' distance to market, farmers' association with agricultural related institutions, number of farm plots under cultivation, past climate change experience, access to climate information, belief in climate change and attitudes towards adaptation. The findings of this study provide insights into designing agricultural adaptation strategies and integrating them in climate change programs and policies.

Keywords: adaptation strategies, agriculture, climate change, endogenous switching, Nepal.

1. Introduction

Climate change's significant effect on agriculture is due to its direct dependency on climate sensitive parameters such as temperature, water, and soil (Maraseni et al. 2012; Parry et al. 2004; Wheeler and Von Braun, 2013). The IPCC fifth assessment report states that climate trends have negatively affected crop production in many of the world's regions (IPCC 2014). In particular, a number of studies have revealed that the yield of most crops decreases as the temperature increases (Challinor et al. 2014; Lobell and Field 2007; Sarker et al. 2014). Agriculture in the least developed countries such as Nepal is relatively more vulnerable to the adverse impacts of climate change due to its higher exposure to extreme weather events, poor production environment, and lack of farmers' knowledge and resources for adaptation (Adger et al. 2003; Aryal et al. 2014, 2016; Huq et al. 2004; Islam et al. 2016; Morton 2007).

In Nepal, the agriculture and forestry sectors contribute approximately 31% of total gross domestic product (GDP) and employ approximately 70% of the population (MoF 2016). Farmers are of the subsistence type with an average land holding size of only 0.8 ha. Nearly two-thirds of the cultivated area is rain-fed (MoAD 2012). Climate change and climate variability therefore have severe consequences for these farmers who rely on weather dependent rain-fed agriculture for their livelihoods (Gentle and Maraseni 2012). The observed impacts of climate change in Nepal include temperature increase, erratic rainfall, unpredictable monsoon seasons, increased occurrence of storms, landslides and droughts (Devkota et al. 2013; Khanal 2014; Gentle and Maraseni 2012; MoE, 2010). These impacts have adversely affected crop production thereby increasing food and livelihood insecurity (Malla 2009; MoE 2010). For instance, in 2012/13, rice, maize and millet production fell by 11.3%, 8.3% and 3% respectively, due to inadequate rainfall and prolonged droughts (MoF 2013).

The relationship of climate change and food production depends to a large degree on when and which adaptation strategies are taken (IPCC 2014). Thus, identification of effective adaptation strategies, their dissemination and adoption at a wider level, is crucial to deal with the current and future impacts of climate change and variability. There is increasing evidence that farmers have commenced adapting to observed changes in climate, in particular through changing the timing of farm operations, growing diverse crop species and varieties, adopting soil and water conservation practices and agroforestry (Asseng and Pannell, 2013; Devkota et al. 2017; Niles et al. 2016; Zhang et al. 2015). Such adaptation measures can minimize the adverse impacts of climate change and contribute substantially to reducing the food insecurity of farming households (Challinor et al. 2014; Di Falco and Veronesi 2013).

Over the last few years, numerous studies have examined the impact of climate change adaptation in agricultural production (for e.g., Di Falco et al. 2011; Finger et al. 2011; Rosenzweig and Parry 1994). However, many of these studies have focused their analysis at the macro level and taken into account only a few of the adaptation strategies (Challinor et al. 2014; Waha et al. 2013). Several studies have investigated the impact of adaptation on food production at the household and farm level (Di Falco et al. 2011; Huang et al. 2015; Khanal et al. 2018). These studies find that adaptation to climate change through adjustments in farmers' management practices significantly increases agricultural production. However, these studies consider all the adaptations as a binary choice of adapting or not adapting to climate change without distinguishing the effect of different adaptation strategies.

It has been found that farmers make adjustments in agricultural management practices, including the employment of technology, to deal with both climatic and non-climatic stresses. However, one of the challenges in studying the impact of climate change adaptation in food production is the identification of true adaptation. That is because many adjustments that farmers make in their farming practices do not necessarily represent adaptation to climate change (Huang et al. 2015; Lobell 2014). Furthermore, farmers' responses to climate change vary across locations depending on specific climatic, social, economic, and institutional conditions (Below et al. 2012; Deressa et al. 2009; Khanal et al. 2018). Hence, investigation of location specific genuine adaptation practices and their impact on food production is important for the effective adaptation planning at the local level.

The impacts of adaptations on food production can be examined employing a number of approaches. First, we can compare the actual mean agricultural production per hectare between farming households that employ particular adaptation strategies and those that do not. A second possible approach could be estimating a linear regression model of production including the adoption of adaptation strategies as a binary variable (Di Falco and Veronesi 2013). However, both approaches assume that adaptation to climate change is exogenously determined, whereas it can, potentially, be an endogenous variable (Di Falco et al. 2011). That is, the difference in farming households' food productivity may be caused by unobservable characteristics of the farming households.

In this study, we first identify the true climate change adaptation practices undertaken by Nepalese farming households. This is done by linking farmers' perception of changes in local climatic conditions, their impact on agricultural production and the adjustments they have made in response to these impacts. The driving forces behind farming households' decisions to adopt climate change adaptations is then examined as is the impact of different types of adaptations on farming households' food productivity. We employ the endogenous switching regression model to take into account selectivity bias and to investigate the differential impact of specific adaptation strategies on adopters and non-adopters.

We contribute to the existing literature on climate change adaptation in agriculture in four ways. First, we identify the true adaptations to climate change by linking climate change, impacts and actual adaptations. Second, we examine the impact of different types of adaptation strategies on food productivity at the farming household level. Third, we employ the endogenous switching regression model with counterfactual analysis in order to investigate what farming households would have produced if they had not adopted a specific adaptation strategy. Finally, from this Nepalese case study, a contribution is made to the empirical evidence relating to climate change and its impact on food productivity.

2. Methodology

2.1 Study area, data, and descriptive statistics

The data used in this study were collected in a face-to-face survey conducted from October 2015 to January 2016 in six districts of Nepal. These districts are Chitwan and Rupandehi from the Terai region, Kaski and Dhading from the Hill region, and Mustang and Rasuwa from the Mountain region[1]. The field study was conducted by means of randomly selecting two village development committees (VDCs)[2] in each district. The selection of farming households from the VDC involved two steps. First, four wards in each VDC were selected randomly. The details of selected VDCs and wards are presented in Supplementary Table 1. Then, we selected 15 farming households[3] from each ward through simple random sampling, producing a total

[1]Nepal is divided into three distinct agro-ecological regions, namely the Terai in the south, the Hill in the center, and the Mountain in the north.
[2]A VDC is an administrative unit in Nepal similar to municipality which is further divided into nine wards. Each ward constitutes one to several villages.
[3]The households in the selected VDC that were not involved in farming activities were excluded from the sampling frame. We asked four to five villagers to identify the households involved in farming. People in

sample size of 720. This represented 17.4% of the total farming households in the selected wards[4]. Of the total sample, we excluded 16 observations from the analysis due to missing information on selected variables under study.

Two different methods were used for data collection. First, we conducted one focus group discussion (FGD) in each VDC. The participants – numbering around 8-10 farmers - were long term residents of the study area. From them we collected information related to general features of the villages under study, farmers' perceptions about climate change and adaptation strategies. To ensure that the adaptation practices that farmers adopt were a consequence of climate change and not due to other pressures, we asked three contingent questions[5]; 1) Do you perceive any changes in the local climatic conditions in the last 15-20 years? If yes, what are they? 2) What has been the impact of these changes on agricultural production? 3) What have you done to deal with these changes? The identified adaptation practices were included in the household survey questionnaire used to examine the actual adaptations by the sampled households. We conducted household survey interviews in the Nepali language gathering information on farming households' socio-economic characteristics, input use, outputs, farmers' perceptions, attitudes, and beliefs on climate change and climate change adaptation practices adopted by farmers on their farms.

2.2 Empirical strategy

We employed the endogenous switching regression model to estimate the impact of adoption of different types of adaptation strategies on food productivity. This method takes into account both observed and unobserved factors when estimating the impact of adoption. Food

---

Nepalese villages, by nature of their close proximity to each other, are familiar with almost all families in their village. Consequently listing of households involved in farming proved a relatively easy task for them.

[4]The total number of farming households in the selected 48 wards was 4,128.

5 These questions were also included in the household survey questionnaire.

productivity was simply calculated as the ratio of the total value of agricultural production in Nepalese rupees (NRs) to the cultivated area of the household expressed in hectares.

Following Di Falco et al (2011) and Khanal et al (2018), a switching regression was performed in two stages. In the first stage, selection of an adaptation strategy is specified by means of a binary model. The equations for the outcome of interest - in this case food productivity - are modeled for both adopters and non-adopters conditional on selection. We assume that a rational farmer *i* decides to adopt a particular adaptation strategy if the expected food production derived from adoption (Y_{Ai}) is greater than the production received from non-adoption (Y_{Ni}). However, given that the researcher does not observe the expected production due to adoption as perceived by the farmers, but only the adoption of an adaptation strategy, the adoption decision (A) is treated as dichotomous: A =1 if $Y_{Ai} > Y_{Ni}$ and A = 0 otherwise. Thus, since the farmers' characteristics and adoption attributes are observed during the survey period, the production derived from the adoption of climate change adaptation strategies can be represented by a latent variable A*. This is not, however, observed but can be expressed as a function of the observed characteristics and attributes.

$$A_i^* = Z_i\alpha + \eta_i \text{ with } A_i = 1 \text{ if } A_i^* > 0 \text{ and 0 otherwise} \quad (1)$$

where α is a vector of model parameters to be estimated and η is a vector of normally distributed mean zero random error terms. The vector Z represents farm and household characteristics which influence farmers' decisions to employ an adaptation strategy. We include a number of variables based on the review of empirical literature on the determinants of farmers' adaptation (Below et al. 2012; Deressa et al. 2009; Fisher et al. 2015; Haden et al. 2012). Specifically, we include household characteristics such as age and education of household head, family size, family members' involvement in non-farm work, and farm characteristics such as the number of cultivated farm plots and whether the household's farming was affected by drought or flood. We used age and education of the household head rather than of all the household members. This is because in rural areas of Nepal household decisions are made by the household head (Dhakal et al. 2015). We also included information, resources, and belief related variables such as distance to market, family members' association with agricultural related institutions, access to climate information, belief in climate change and adaptation success (Table 1).

In the second stage, separate outcome equations are specified for adopters and non-adopters.

$$Y_{Ai} = X_{Ai}\beta_A + \varepsilon_{Ai} \qquad \text{if } Ai = 1 \qquad (2a)$$

$$Y_{Ni} = X_{Ni}\beta_N + \varepsilon_{Ni} \qquad \text{if } Ai = 0 \qquad (2b)$$

where Y_{Ai} and Y_{Ni} are the food production[6] per hectare specified in a log for adopters and non-adopters respectively. X is a set of explanatory variables that include production inputs specified in log (e.g., land, labor, fertilizers, capital), and household and farm characteristics included in Z. The vectors β_A and β_N are the parameters to be estimated. For the model to be identified, it is required that there is at least one variable in the adoption equation that does not appear in the outcome equation. The variables representing access to climate information, climate beliefs and success of adaptation beliefs, are used as the instrument variables. While these variables are expected to affect adoption decisions, it is assumed that these do not affect food productivity directly.

[6] The output variable 'food production' is the total value of agricultural production measured as the sum of the value of all cereal, leguminous and oil seed crops produced by a household in year 2014/15. This includes the value of both sold quantities and kept quantities in the house for family consumption.

The three error terms η, ε_A and ε_N in equations (1), (3a) and (3b) are assumed to have a trivariate normal distribution, with zero mean and the following covariance matrix:

$$Cov(\eta, \varepsilon_A, \varepsilon_N) = \Sigma = \begin{bmatrix} \sigma_\eta^2 & \sigma_{\eta A} & \sigma_{\eta N} \\ \sigma_{A\eta} & \sigma_A^2 & \sigma_{AN} \\ \sigma_{N\eta} & \sigma_{NA} & \sigma_N^2 \end{bmatrix}$$

where Var (ε_A) = σ_A^2, Var (ε_N) = σ_N^2 and Var (η) = σ_η^2, Cov ($\varepsilon_A, \varepsilon_N$) = σ_{AN}, and Cov (ε_A, η) = $\sigma_{A\eta}$, and Cov (ε_N, η) = $\sigma_{N\eta}$. Since Y_{Ai} and Y_{Ni} are not observed simultaneously, the covariance between ε_{Ai} and ε_{Ni} is not defined. The error term of the sample selection equation (1) η_i is correlated with the error terms of the outcome equations (2a) and (2b). Hence the expected values of ε_{Ai} and ε_{Ni} conditional on the sample selection are non-zero (Lee and Trost 1978), are given as:

$$E[\varepsilon_{Ai}|A_i = 1] = \sigma_{A\eta} \frac{\varphi(Z_i\alpha)}{\phi(Z_i\alpha)} = \sigma_{A\eta}\lambda_{Ai}$$

and,

$$E[\varepsilon_{Ni}|A_i = 0] = -\sigma_{N\eta} \frac{\varphi(Z_i\alpha)}{1-\phi(Z_i\alpha)} = \sigma_{N\eta}\lambda_{Ni}$$

where $\varphi(.)$ and $\phi(.)$ are the probability density and the cumulative distribution function of the standard normal distribution, respectively. The terms λ_A and λ_N refer to the inverse Mills ratio evaluated at $Z_i\alpha$ and are incorporated into outcome equations to account for sample selection bias. In this study, we used the full information maximum likelihood method suggested by Lokshin and Sajaia (2004) which simultaneously estimates the two equations, that is, the selection and outcome equations. The signs and significance levels of the correlation coefficients (ρ) from the estimates are of particular interest. These are the correlation coefficients between the error term η_i of the selection equation and error terms ε_A and ε_N of the outcome equations (2a) and (2b) respectively. Specifically, there is endogenous switching, if either ρ_A or ρ_N is significantly different from zero, which would result in selection bias.

In this study, our main interest is to estimate the treatment effect of adoption of climate change adaptation. That is, how the adoption of different adaptation strategies impacts on food productivity. The endogenous switching regression method can be used to compare expected food productivity with the counterfactual hypothetical case that farming households did not adopt adaptation strategies. This can be represented as follows:

$$E[Y_{Ai}|A_i = 1] = X_{Ai}\beta_A + \sigma_{A\eta}\lambda_{Ai} \quad (3)$$

$$E[Y_{Ni}|A_i = 0] = X_{Ni}\beta_N + \sigma_{N\eta}\lambda_{Ni} \quad (4)$$

$$E[Y_{Ni}|A_i = 1] = X_{Ai}\beta_N + \sigma_{N\eta}\lambda_{Ai} \quad (5)$$

and

$$E[Y_{Ai}|A_i = 0] = X_{Ni}\beta_A + \sigma_{A\eta}\lambda_{Ni} \quad (6)$$

The average treatment effect on the treated (TT) (that is, the change in the food productivity due to the practice of adaptation) can be computed from equations (3) and (5) as:

$$TT = E[Y_{Ai}|A_i = 1] - E[Y_{Ni}|A_i = 1] = X_{Ai}(\beta_A - \beta_N) + (\sigma_{A\eta} - \sigma_{N\eta})\lambda_{Ai} \quad (7)$$

Similarly, we can compute the effect of the treatment on the untreated (TU) for the farming households that actually did not adopt an adaptation strategy, as the difference between equations (4) and (6).

$$TU = E[Y_{Ni}|A_i = 0] - E[Y_{Ai}|A_i = 0] = X_{Ni}(\beta_N - \beta_A) + (\sigma_{N\eta} - \sigma_{A\eta})\lambda_{Ni} \quad (8)$$

We repeated the above mentioned procedure five times to estimate the effect of five different types of adaptation strategies on food productivity.

3. Results and discussion

3.1 Descriptive statistics

Table 1 presents descriptive statistics for the surveyed households. The average land holding size was 0.56 ha. On average, the value of food produced by a farming household per hectare was NRs 90,585 (US$854)[7] utilizing 105 days of labour, 246 kg of chemical fertilizers, and capital expenditure of NRs 7,496 (US$70.7). Table 2 presents the various adaptation practices adopted by farming households on their farms. Details of farmers' perceived climate change impacts and adaptation strategies are presented in Annex 1. We categorized the adaptation practices into five adaptation strategies: crop and varietal adjustment, adjustment in the timing of farm operations, soil and water management, fertilizer management, and off-farm adjustment. The household survey results showed that some 91% of the farming households had undertaken at least one adaptation practice in response to the changing climate. Specifically, 53% of the farming households adjusted crop species and varieties, 51% adopted soil and water conservation practices, 48% improved or increased the fertilizer use, 45% made an adjustment in the timing of farm operations and 18% made at least one off-farm adjustment.

3.2 Determinants of climate change adaptation

Table 3 presents the results of the adoption equations representing determinants of adoption of five adaptation strategies: crop/varietal adjustment, farm operation time adjustment, soil and water management, fertilizer management, and off-farm adjustment practices. The coefficient of education is positive and significant in all the models implying that better educated farm households are more likely to implement adaptation strategies to minimize climate change impacts. Similar results have been reported in Ethiopia (Deressa et al. 2009) and Bangladesh (Alam et al. 2016). However, the education level of farmers in our study area is relatively low with the average years of schooling of the household head being approximately seven years. This indicates the need for easier access to education among farmers in order to promote the wider employment of adaptation strategies. The drought/flood variable is also positive and significant in all the models. This suggests that households affected by droughts or floods in

[7] 1 USD = NRs 106.07 (from the website of the Nepal Rastra Bank, accessed on 12/01/2016)

the last five years are more likely to employ adaptation strategies on their farms than those that are not affected. Empirical evidence from Bangladesh supports this findings. A study shows that the likelihood of farmers adopting supplementary irrigation and switching to low water demanding crops increases with the increase in drought severity (Alauddin and Sarker 2014).

Among other household characteristics, both age and family size play important roles in the adoption of some strategies. Specifically, older farmers are more likely to adopt all four of the key strategies except crops and varietal adjustment. It can be argued that older farmers are more experienced in farming and have more knowledge and skills in employing adaptation practices. However, the existing literature shows a mixed impact of age of farmers on adaptation decision (Deressa et al. 2009; Hassan and Nhemachena 2008; Piya et al. 2013). Contrary to our expectation that large families have a greater labour force which would induce households to adopt labour intensive adaptations, the results indicate that the smaller the family size is, the more likely it is to undertake soil and water management, fertilizer management, and off-farm adjustments. This finding is inconsistent with that of Deressa et al. (2009) and Hassan and Nhemachena (2008). This may be due to people in the rural areas of Nepal moving out of agriculture in search of non-farm opportunities (Khanal et al. 2015). It has been argued that participation in non-farm activities impede the involvement in farm production activities (Abdulai and Huffman 2014). Our findings further suggest that the households that are located nearby market are more likely to employ off-farm adaptation measures. This may be due to greater access to information in off-farm employment.

The coefficient of ‘variable institutions’ suggests that association of family members with agricultural related organizations increases the likelihood of making adjustment in the timing of farm operations in response to climate change impacts. This supports the argument that farmers get information on improved farm management practices and innovations from farmers' organizations and social networks (Abdulai and Huffman 2014).

The sign for 'variable plots' is positive in all the models, but, is significant only for soil and water management. This indicates that households cultivating a larger number of plots are more likely to undertake soil and water management practices. This positive association may be because households with more farm plots have the scope to take a risk in adopting innovations on at least in one of their farm plots (Khanal et al. 2018).

Interestingly, the effects of climate information, climate belief, and adaptation beliefs are all positive in all cases and significant in most cases. The coefficients of climate information indicate that farmers that receiving information on climate change are more likely to undertake crop and varietal adjustments, farm operation time adjustments and off-farm adjustments. This positive effect of access to climate information on the adoption of adaptation strategies is consistent with other studies (Alam et al. 2016; Deressa et al. 2009; Khanal et al. 2018). Nevertheless, only 33% of farmers in our study area had received information on climate change indicating the necessity of providing climate related information to farmers in order to increase the uptake of adaptation strategies. Furthermore, those farmers who believe that local climatic conditions have changed are more likely to adapt. Similarly, farmers who believe that adaptation minimizes the adverse impact of climate change on agricultural production are more likely to employ crop and varietal adjustment, soil-water management and fertilizer management.

3.3 Impacts of adaptation on food productivity

As already outlined, we employed an endogenous switching regression models to account for the endogeneity problem in examining the impact of different types of adaptation strategies in food production. The results, presented in Table 4, account for the endogenous switching in the production functions. An interesting finding is the signs and significances of the covariance terms ρ_A and ρ_N. The results show that the covariance terms for the non-adopters are statistically significant in most models, indicating that self-selection occurred in adaptation. Thus, employment of adaptation strategies to minimize climate change impacts do not have the same effect on the non-adopters, if they choose to adopt. Moreover, the differences in the coefficients of the outcome equations between the farming households that adopted and those that did not adopt suggest the presence of heterogeneity in the sample.

Table 5 presents the value of agricultural production per hectare under actual and counterfactual conditions. The last two columns of Table 5 presents the impact of each adaptation strategy on agricultural production, which is the treatment effect, calculated as the difference between columns 3 and 4. Importantly, we find the statistically a significant impact on agricultural production of crop and varietal adjustment, farm operation time adjustment and soil and water management. However, we find no statistical evidence of an impact of fertilizer management and off-farm adjustment on agricultural production.

The expected value of agricultural production per hectare by farming households that undertook crop and varietal adjustment is approximately NRs 94,818 (US$893.92), compared to NRs 79,133 (US$746.05) for the non adopting group of farming households. This indicates that, on average, farming households that adopted crop and varietal adjustment strategies produced about 20% more than those that did not adopt. Similarly, those adopting farm operation time adjustments, soil and water management, fertilizer management, and off-farm adjustments produced about 21%, 26%, 14% and 6% more than those that did not adopt, respectively. Furthermore, the results show that the households that actually adopted crop and varietal adjustments would have produced about 26% less if they had not adapted. As well, the households that actually adopted farm operation time adjustments, soil and water management, fertilizer management, and off-farm adjustments would have produced about 11%, 22%, 6%, and 5% less if they had not adopted. Moreover, farming households which actually did not adopt crop and varietal adjustments would have produced about 12% more if they had adopted. The households which did not adopt farm operation adjustments, soil and water management, fertilizer management, and off-farm adjustments, would have produced about 24%, 34%, 9%, and 7% more if they had adopted.

The results of this study support the findings of many studies (e.g., Di Falco et al. 2011; Finger et al. 2011; Huang et al. 2015; Khanal et al. 2018) which report a positive impact of adoption of climate change adaptation practices on crop production. However the findings of this study are inconsistent with that of Di Falco and Veronesi (2013) who produced no statistical evidence of the impact of changing crops, water and soil conservation to the farm households' net revenues, when implemented in isolation. Our study reveals that 91% of the farming households had employed at least one adaptation strategy to mitigate the adverse impact of climate change. However, the results show that only a few farmers had employed a wide range of adaptation strategies (Table 2). This suggests that a large percentage of farmers in Nepal have an unexplored opportunity to enhance farm productivity by employing various adaptation strategies.

4. Conclusions

The findings of this study show that education has a positive and significant impact on the adoption of all five adaptation strategies. This draws attention to the importance of enhancing farmers' education. Other socioeconomic characteristics such as the age of the household head (decision-maker), family size, distance to market, association with agricultural related institutions, and the number of farm plots play a significant impact on the adoption of adaptation strategies. Consequently, policies aimed at planning and implementing adaptation programs need to emphasize the crucial role of household socioeconomic characteristics. They should therefore aim at promoting adaptation strategies through research based on farmers' social, economic and attitudinal characteristics. Past climate change experience, climate information, climate belief and adaptation beliefs play important roles in farmers' adaptation to climate change. These results indicate the importance of raising awareness and capacity building activities in rural areas of Nepal which can enhance farmers' awareness of climate change issues.

Adoption of adaptation strategies is found to significantly increase agricultural production. Among the adaptation strategies, the adoption of soil and water management are shown to have the largest impact on food production followed by adjustment in the timing of farm operations and crop and varietal adjustment. In addition, on average, households that did not employ adaptation strategies, would also have benefited more from the adoption of adaptation strategies.

A limitation of this study is that we have considered adaptation strategies in isolation. In practice, an individual farming household may implement multiple adaptation strategies simultaneously. We therefore recommend further studies to assess the impact of different combinations of adaptation strategies on farm productivity. Since agriculture is one of the major sources of global greenhouse gas emissions (Maraseni et al. 2010; Maraseni et al. 2009; Maraseni and Qu 2016), we see a need for studies to examine the extent to which farmers' adaptation practices contribute to carbon sequestration. With such data, a valuable contribution to policy-decision making could be made through examining the various climate change impacts and their interactions with and without adaptation strategies (see, for example, Halkos and Tsilika, 2017).

References

Abdulai A, Huffman W (2014) The adoption and impact of soil and water conservation technology: An endogenous switching regression application. *Land Economics 90*(1): 26-43.

Adger WN, Huq S, Brown K, Conway D, Hulme M (2003) Adaptation to climate change in the developing world. *Progress in Development Studies 3*(3): 179-195.

Alam GM, Alam K, Mushtaq S (2016) Influence of institutional access and social capital on adaptation decision: Empirical evidence from hazard-prone rural households in Bangladesh. *Ecological Economics 130*: 243-251.

Alauddin M, Sarker MAR (2014) Climate change and farm-level adaptation decisions and strategies in drought-prone and groundwater-depleted areas of Bangladesh: an empirical investigation. *Ecological Economics 106:* 204-213.

Aryal S, Cockfield G, Maraseni TN (2014) Vulnerability of Himalayan transhumant communities to climate change. *Climatic Change 125*(2): 193-208.

Aryal S, Cockfield G, Maraseni TN (2016) Perceived changes in climatic variables and impacts on the transhumance system in the Himalayas. *Climate and Development 8*(5): 435-446.

Asseng S, Pannell DJ (2013) Adapting dryland agriculture to climate change: Farming implications and research and development needs in Western Australia. *Climatic Change 118*(2): 167-181.

Below TB, Mutabazi KD, Kirschke D, Franke C, Sieber S, Siebert R, Tscherning K (2012) Can farmers' adaptation to climate change be explained by socio-economic household-level variables? *Global Environmental Change 22*(1): 223-235.

Challinor A, Watson J, Lobell D, Howden S, Smith D, Chhetri N (2014) A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change 4*: 287-291.

Deressa TT, Hassan RM, Ringler C, Alemu T, Yesuf M (2009) Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global Environmental Change 19*(2): 248-255.

Devkota RP, Maraseni TN, Cockfield G, Devkota L P (2013) Flood vulnerability through the eyes of vulnerable people in mid-western Terai of Nepal. *Journal of Earth Science and Climactic Change 4*(1): 1-7.

Devkota RP, Pandey VP, Bhattarai U, Shrestha H, Adhikar, S, Dulal KN (2017) Climate change and adaptation strategies in Budhi Gandaki River Basin, Nepal: a perception-based analysis. *Climatic Change 140*(2): 195-208.

Dhakal A, Cockfield G, Maraseni TN (2015) Deriving an index of adoption rate and assessing factors affecting adoption of an agroforestry-based farming system in Dhanusha District, Nepal. *Agroforestry Systems 89*(4): 645-661.

Di Falco S, Veronesi M (2013) How can African agriculture adapt to climate change? A counterfactual analysis from Ethiopia. *Land Economics 89*(4): 743-766.

Di Falco S, Veronesi M, Yesuf M (2011) Does adaptation to climate change provide food security? A micro-perspective from Ethiopia. *American Journal of Agricultural Economics 93*(3): 829-846.

Finger R, Hediger W, Schmid S (2011) Irrigation as adaptation strategy to climate change-a biophysical and economic appraisal for Swiss maize production. *Climatic Change 105:* 509-528.

Fisher M, Abate T, Lunduka RW, Asnake W, Alemayehu Y, Madulu RB (2015) Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *Climatic Change 133*(2): 283-299.

Haden VR, Niles MT, Lubell M, Perlman J, Jackson LE (2012) Global and local concerns: what attitudes and beliefs motivate farmers to mitigate and adapt to climate change? *PloS Pne 7*(12).

Halkos G and Tsilika, K (2017) Climate change effects and their interactions: An analysis aiming at policy implications. *Economic Analysis and Policy 53*: 140-146.

Hassan R, Nhemachena C (2008) Determinants of African farmers' strategies for adapting to climate change: Multinomial choice analysis. *African Journal of Agricultural and Resource Economics 2*(1): 83-104.

Huang J, Wang Y, Wang J (2015) Farmers' Adaptation to Extreme Weather Events through Farm Management and Its Impacts on the Mean and Risk of Rice Yield in China. *American Journal of Agricultural Economics 97*(2): 602-617.

Huq S, Reid H, Konate M, Rahman A, Sokona Y, Crick F (2004) Mainstreaming adaptation to climate change in least developed countries (LDCs). *Climate Policy 4*(1): 25-43.

IPCC (2014) *Climate Change 2014:* Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Islam M, Kotani K, Managi S (2016) Climate perception and flood mitigation cooperation: A Bangladesh case study. Economic Analysis and Policy 49: 117-133.

Khanal U (2014) Perception and adaptation of the producers to the impacts of climate change in apple production: an assessment of Mustang district of Nepal. *Journal of Agriculture and Environment 15:* 11-17.

Khanal U, Alam K, Khanal RC, Regmi PP (2015) Implications of out-migration in rural agriculture: a case study of Manapang village, Tanahun, Nepal. *The Journal of Developing Areas 49*(1): 331-352.

Khanal U, Wilson C, Hoang VN, Lee B (2018) Farmers' Adaptation to Climate Change, Its Determinants and Impacts on Rice Yield in Nepal. *Ecological Economics 144:* 139-147.

Khanal U, Wilson C, Lee B, Hoang VN (2018) Do climate change adaptation practices improve technical efficiency of smallholder farmers? Evidence from Nepal. Climatic change, doi: 10.1007/s10584-018-2168-4

Lee LF, Trost RP (1978) Estimation of some limited dependent variable models with application to housing demand. *Journal of Econometrics 8*(3): 357-382.

Lobell DB (2014) Climate change adaptation in crop production: beware of illusions. *Global Food Security 3*(2): 72-76.

Lobell DB, Field CB (2007) Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters 2*(1): 014002.

Lokshin M, Sajaia Z (2004) Maximum likelihood estimation of endogenous switching regression models. *Stata Journal 4:* 282-289.

Malla G (2009) Climate change and its impact on Nepalese agriculture. *Journal of Agriculture and Environment 9:* 62-71.

Maraseni T, Mushtaq S, Reardon-Smith K (2012) Climate change, water security and the need for integrated policy development: the case of on-farm infrastructure investment in the Australian irrigation sector. *Environmental Research Letters 7*(3): 034006.

Gentle P, Maraseni TN (2012) Climate change, poverty and livelihoods: adaptation practices by rural mountain communities in Nepal. *Environmental science & policy 21*: 24-34.

Maraseni TN, Cockfield G, Maroulis J (2010) An assessment of greenhouse gas emissions: implications for the Australian cotton industry. *The Journal of Agricultural Science 148*(5): 501-510.

Maraseni TN, Mushtaq S, Maroulis J (2009) Greenhouse gas emissions from rice farming inputs: a cross-country assessment. *The Journal of Agricultural Science 147*(2): 117-126.

Maraseni TN, Qu J (2016) An international comparison of agricultural nitrous oxide emissions. *Journal of Cleaner Production 135:* 1256-1266.

MoAD (2012) *Statistical Information on Nepalese Agriculture 2011/12.* . Government of Nepal, Ministry of AgriculturalDevelopment, Agri-Business Promotion and Statistics Division, Agri statistics Section, Singha Durbar, Kathmandu, Nepal.

MoE (2010) *National Adaptation Programme of Action to Climate Change*. Ministry of Environment, Kathmandu, Nepal.

MoF (2013) *Economic Survey: Fiscal Year 2012/13*. Ministry of Finance, Kathmandu, Nepal.

MoF (2016) Economic Survey: Fiscal Year 2015/16. Ministry of Finance, Kathmandu, Nepal.

Morton JF (2007) The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences 104*(50): 19680-19685.

Niles MT, Brown M, Dynes R (2016) Farmer's intended and actual adoption of climate change mitigation and adaptation strategies. *Climatic Change 135*(2): 277-295.

Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change 14*(1): 53-67.

Piya L, Maharjan KL, Joshi NP (2013) Determinants of adaptation practices to climate change by Chepang households in the rural Mid-Hills of Nepal. *Regional Environmental Change 13*(2): 437-447.

Rosenzweig C, Parry ML (1994) Potential impact of climate change on world food supply. *Nature 367*(6459): 133-138.

Sarker MAR, Alam K, Gow J (2014) Assessing the effects of climate change on rice yields: An econometric investigation using Bangladeshi panel data. Economic Analysis and Policy *44*(4): 405-416.

Waha K, Müller C, Bondeau A, Dietrich J, Kurukulasuriya P, Heinke J, Lotze-Campen H (2013) Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. *Global Environmental Change 23*(1): 130-143.

Wheeler T, Von Braun J (2013) Climate change impacts on global food security. *Science 341*(6145): 508-513.

Zhang HL, Zhao X, Yin XG, Liu SL, Xue JF, Wang M, Pu C, Lal R, Chen F (2015) Challenges and adaptations of farming to climate change in the North China Plain. *Climatic Change 129*(1-2): 213-224.

Table 1. Variable names, definitions and descriptive statistics for the sample

Variable	Description	Sample mean	Std. Dev.
Output	Value of agriculture production in NRs/hectare	90584.93	83231.43
Land	Land area under cultivation in hectare	0.56	0.62
Labour	Quantity of labour use per hectare (days)	105.52	86.73
Fertilizers	Chemical fertilizers use per hectare (kg)	245.80	447.86
Capital	Capital expenditure (pesticides, seed, irrigation etc.) per hectare (NRs)	7495.92	16060.93
Age	Age of the household head in years	45.88	13.95
Education	Household head's education measured in number of years of schooling	6.63	4.21
Family size	Total number of members in the family	6.04	2.53
Non-farm	Dummy = 1 if any member in the family involved in non-farm job, 0 otherwise	0.68	0.46
Market	Distance from house to market in kilometers (km)	8.07	10.51
Institution	Dummy = 1 if any member in the household was member of agricultural related groups and organizations, 0 otherwise	0.62	0.50
Plots	Number of farm plots under cultivation	2.91	2.13
Drought/flood	Dummy = 1 if the household was affected by drought or flood during the last five years, 0 otherwise	0.35	0.48
Climate information	Dummy = 1 if the household received information on climate change, 0 otherwise	0.33	0.47
Climate belief	Dummy = 1 if the respondent believes climate has changed in the local area, 0 otherwise	0.76	0.42
Adaptation belief	Dummy = 1 if the respondent believes adaptation minimizes negative climate change impacts in agriculture, 0 otherwise	0.69	0.46

Table 2. Farmers' adaptation strategies

Adaptation category	Adaptation practices	Percent of respondents
No adaptation	No adjustment to climate change impacts	8.89
Crop/varietal adjustment	Grow drought tolerant/short duration/pest resistant crops species or varieties, crop rotation, intercropping/mixed cropping[a], change planting locations of crops	53.21
Farm operations time adjustment	Change planting/ harvesting/ weeding/ pesticide application date and time	45.49
Soil and water management	Mulching, cover crops, reduce tillage, terrace construction, agroforestry[b], rain water harvesting, flood control, improve/increase irrigation	51.07
Fertilizer management	Improve/increase chemical fertilizer or farm yard manure use	48.15
Off-farm adjustment	Keep more livestock, livelihood diversification	18.29

[a]Two or more crops grown simultaneously in a same piece of land.

[b]The practice of growing trees and crops in interacting combinations.

Table 3. Probit model estimates of adoption of climate change adaptation strategies

Variable	Crop/varietal adjustment	Farm operation time adjustment	Soil and water management	Fertilizer management	Off-farm adjustment
Constant	-0.008	-1.062**	-1.108**	-1.157**	-2.746***
	(0.489)	(0.541)	(0.533)	(0.538)	(0.593)
Land (log)	0.155**	-0.080	0.176**	-0.038	-0.061
	(0.078)	(0.079)	(0.080)	(0.077)	(0.086)
Labour(log)	0.127	0.217**	0.260***	0.140	0.120
	(0.084)	(0.095)	(0.096)	(0.095)	(0.101)
Fertilizers (log)	0.010	-0.087**	0.115***	0.051	0.029
	(0.043)	(0.044)	(0.044)	(0.044)	(0.049)
Capital (log)	-0.030	-0.035	-0.099	-0.047	0.030
	(0.062)	(0.068)	(0.069)	(0.071)	(0.078)
Age	-0.003	0.008**	0.008*	0.009**	0.008*
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)
Education	0.034**	0.032**	0.025*	0.047***	0.049***
	(0.013)	(0.014)	(0.013)	(0.014)	(0.015)
Family size	-0.028	0.016	-0.054***	-0.081***	-0.053**
	(0.019)	(0.020)	(0.021)	(0.022)	(0.024)
Non-farm	0.001	0.026	0.122	-0.058	-0.005
	(0.103)	(0.109)	(0.111)	(0.109)	(0.117)
Market	0.002	0.001	0.002	0.001	-0.015**
	(0.005)	(0.005)	(0.005)	(0.005)	(0.007)
Institution	-0.071	0.303**	0.050	0.181	0.047
	(0.109)	(0.126)	(0.119)	(0.117)	(0.116)
Plots	0.035	0.011	0.043*	0.025	0.030
	(0.026)	(0.025)	(0.026)	(0.021)	(0.028)
Drought /flood	0.265**	0.746***	0.800***	0.941***	0.925***
	(0.108)	(0.116)	(0.117)	(0.116)	(0.120)
Climate information	0.229***	0.208**	0.002	0.042	0.209**
	(0.081)	(0.092)	(0.103)	(0.104)	(0.109)
Climate belief	0.165*	0.338***	0.271**	0.223**	0.405***
	(0.094)	(0.122)	(0.114)	(0.113)	(0.135)
Adaptation belief	0.235***	0.088	0.220**	0.182*	0.036
	(0.085)	(0.112)	(0.104)	(0.100)	(0.107)
Log likelihood	-1234.47	-1221.35	-1175.74	-1196.67	-1112.58
Likelihood ratio test of independent equations χ^2	25.34***	8.67***	7.68***	9.77***	22.93***

Standard errors in parenthesis. ∗Significant at the 10% level; ∗∗Significant at the 5% level; ∗∗∗Significant at the 1% level.

Table 4. Endogenous switching regression results for impact of adaptation on output

Variable	Crop/varietal adjustment		Farm operation time adjustment		Soil and water management		Fertilizer management		Off-farm adjustment	
	Adopters	Non-adopters	Adopters	Non-adopters	Adopters	Non-adopters	Adopters	Non-adopters	Adopters	Non-adopters
Constant	6.797***	6.368***	8.006***	6.611***	7.288***	7.247***	7.965***	6.860***	7.658***	7.085***
	(0.384)	(0.556)	(0.587)	(0.372)	(0.368)	(0.516)	(0.469)	(0.450)	(0.880)	(0.360)
Land (log)	0.263***	0.301***	0.337***	0.288***	0.233***	0.377***	0.360***	0.245***	0.251***	0.283***
	(0.064)	(0.082)	(0.073)	(0.061)	(0.057)	(0.080)	(0.064)	(0.065)	(0.098)	(0.057)
Labour(log)	0.388***	0.533***	0.420***	0.552***	0.202***	0.793***	0.303	0.649***	0.276***	0.585***
	(0.069)	(0.094)	(0.086)	(0.073)	(0.061)	(0.093)	(0.073)	(0.079)	(0.101)	(0.066)
Fertilizers (log)	0.069**	0.052	0.035	0.121***	0.075**	0.120	0.013***	0.131***	-0.021	0.108***
	(0.032)	(0.046)	(0.044)	(0.037)	(0.030)	(0.044)	(0.035)	(0.038)	(0.054)	(0.031)
Capital (log)	0.270***	0.153**	0.172***	0.207***	0.293***	0.095	0.208***	0.171***	0.296***	0.163***
	(0.050)	(0.070)	(0.060)	(0.050)	(0.045)	(0.069)	(0.054)	(0.059)	(0.078)	(0.049)
Age	0.004	0.006	0.003	0.004	0.008***	0.004	0.011	0.000	0.007	0.003
	(0.003)	(0.004)	(0.004)	(0.003)	(0.003)	(0.004)	(0.003)	(0.004)	(0.005)	(0.003)
Education	0.007	0.001	0.023*	0.001	0.018**	0.003	0.016	0.013	0.021	0.006
	(0.010)	(0.014)	(0.013)	(0.010)	(0.009)	(0.013)	(0.012)	(0.012)	(0.018)	(0.010)
Family size	0.007	-0.056***	-0.020	-0.037**	0.008	-0.075***	-0.028	-0.039**	0.035	-0.047***
	(0.015)	(0.021)	(0.019)	(0.015)	(0.014)	(0.021)	(0.022)	(0.016)	(0.029)	(0.014)
Non-farm	-0.121	0.171	-0.089	0.089	-0.135*	0.137	-0.010	-0.036	-0.157	-0.011
	(0.080)	(0.113)	(0.101)	(0.079)	(0.075)	(0.107)	(0.089)	(0.096)	(0.127)	(0.078)
Market	0.005	-0.003	0.003	0.005	-0.002	0.010**	0.003	0.003	-0.003	0.005
	(0.003)	(0.006)	(0.005)	(0.003)	(0.003)	(0.005)	(0.004)	(0.004)	(0.008)	(0.003)
Institution	0.133	0.221**	0.112	0.209**	-0.022	0.404***	0.051	0.332***	-0.009	0.289***
	(0.085)	(0.119)	(0.102)	(0.086)	(0.075)	(0.118)	(0.096)	(0.101)	(0.148)	(0.083)
Plots	-0.002	0.015	-0.017	0.014	0.008	-0.035	-0.003	0.018	-0.008	0.011
	(0.022)	(0.025)	(0.020)	(0.023)	(0.015)	(0.032)	(0.025)	(0.032)	(0.022)	(0.022)
Drought /flood	-0.228***	-0.240**	-0.103	-0.086	-0.015	-0.210*	-0.233*	-0.394***	-0.200	-0.126
	(0.088)	(0.115)	(0.137)	(0.168)	(0.087)	(0.151)	(0.124)	(0.140)	(0.198)	(0.089)
σ	0.703***	1.099***	0.795***	0.714***	0.626***	0.999***	0.728***	0.911***	0.750***	0.863***
	(0.037)	(0.068)	(0.034)	(0.065)	(0.024)	(0.078)	(0.029)	(0.065)	(0.053)	(0.037)
ρ	0.224	-0.699***	-0.086	0.347	-0.077	0.451***	-0.093	0.387***	-0.211	0.249***
	(0.276)	(0.031)	(0.278)	(0.426)	(0.063)	(0.096)	(0.218)	(0.079)	(0.297)	(0.048)

Standard errors in parenthesis. *Significant at the 10% level; **Significant at the 5% level; ***Significant at the 1% level.

Table 5. Impact of adaptations on expected output (NRs/ha); treatment effects

Adaptation	Sub-samples	Decision stage		Treatment effects	Treatment effects (%)
		To adopt	Not to adopt		
Crop/varietal adjustment	Households that adopted	94818.50	75427.09	TT = 19391.41***	25.71
	Households that did not adopt	88672.98	79133.25	TU = 9539.73**	12.06
Farm operation time adjustment	Households that adopted	107849.6	96744.27	TT = 11105.32**	11.48
	Households that did not adopt	110917.5	89489.59	TU = 21427.91***	23.94
Soil and water management	Households that adopted	97933.97	80124.93	TT = 17809.04***	22.23
	Households that did not adopt	104358.2	77850.02	TU = 26508.14***	34.05
Fertilizer management	Households that adopted	118019.8	110982.2	TT = 7037.62	6.34
	Households that did not adopt	112028.6	103174.3	TU =8854.32	8.58
Off-farm adjustment	Households that adopted	93760.5	89512.98	TT = 4247.52	4.75
	Households that did not adopt	95240.77	88712.39	TU =6528.38	7.36

∗∗Significant at the 5% level; ∗∗∗significant at the 1% level.

Annex 1. Farmers' perception on climate change, its impact in agriculture and adaptation actions

Climatic parameters	Associated hazards	Farmers perceived effects in agriculture	Coping/adaptation actions acted by farmers
Temperature	•Increased summer season temperature •Increased winter season temperature •Increased summer season period •Unpredictable winter season period	•Increased evapotranspiration, thus require more irrigation •More infestation of insects and diseases •Introduction of new insects and diseases •Introduction of new weeds •Reduced grain quality •Crop yield reduction	•Agroforestry •Change planting location of crops/varieties •Cover crops •Crop rotation/Intercropping/mixed cropping •Fallowing •Grow diverse crops/varieties •Grow insect and pest resistant crops/varieties •Grow short duration crops/varieties •Improve fertilizer use •Improve irrigation •Increase number of weeding •Livelihood diversification •Mulching •Reduce crop farming and keep more livestock •Reduce tillage •Use more pesticides •Weather forecasts
Precipitation	•Change in the timing of rainfall including late start of monsoon •Decreased availability of surface and ground water •Long spell drought •Less frequent but heavy rainfall causing flood and landslides	•Delay in crop sowing/planting •Poor germination •Water stress (crop yellowing, drying, reduced growth) •Shortage of irrigation water •Loss of crop due to heavy rainfall •Destruction of water resources and irrigation canal •Soil erosion •Degradation of soil quality •Crop yield reduction	•Agroforestry •Change planting location of crops/varieties •Construction of waterways during heavy rainfall •Cover crops •Grow less water intensive crops/varieties •Grow flood tolerant varieties •Grow short duration crops/varieties •Improve fertilizer use •Improve irrigation •Increase seed rate •Livelihood diversification •Mulching •Rain water harvesting •Reduce tillage •Reduce crop farming and keep more livestock •Shift planting/weeding/harvesting date •Terrace construction •Weather forecasts

Source: Focus Group Discussion

Supplementary Table 1. Selected districts, Village Development Committees (VDCs) and Wards

Agro-ecological regions	Districts	VDCs	Ward numbers
Terai	Chitwan	Phulbari	2, 6, 7, 9
		Sukranagar	3, 4, 6, 7
	Rupandehi	Rudrapur	1, 3, 5, 8
		Souraha Pharsatikar	2, 3, 4, 8
Hill	Dhading	Jogimara	1, 4, 5, 8
		Salyantar	1, 2, 7, 9
	Kaski	Chapakot	3, 5, 7, 9
		Saimarang	1, 4, 6, 8
Mountain	Mustang	Kagbeni	3, 4, 6, 8
		Tukuche	2, 3, 8, 9
	Rasuwa	Bhorle	1, 2, 4, 8
		Syaphru	2, 4, 5, 7