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ORIGINAL ARTICLE

Climate change adaptation in smallholder agriculture: adoption, barriers, determinants, and policy implications

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Abstract
Adaptation to climate change is imperative for the resilience of smallholder agriculture in many developing countries. While studies have focused on climatic impacts on crops and adaptation decisions, barriers to the uptake of adaptation measures by smallholder farmers remain largely unexplored. We empirically quantified the adoption of adaptation measures, as well as barriers to adoption and their determinants for smallholder agriculture in Far Western Province, Nepal, based on a survey of 327 smallholder farmers. We established relationships between barriers and adoption for three different agroecosystems: the Mountain, Hill, and Terai. We then used multiple regression to identify the determinants of barriers in the broader study area, as well as across agroecosystems. We found that adaptation measures such as crop adjustment, farm management, and fertiliser management were practised across all regions. Techno-informational, economic, and environmental barriers were strongly and inversely correlated with adoption of adaptation measures. Adoption, barriers, and determinants varied across agroecosystems. The findings indicate that agricultural development policies must consider climate change adaptation measures tailored to specific agroecosystems in order to most effectively alleviate barriers and promote smallholder resilience.

Keywords Climate change adaptation · Adoption · Barrier · Resilience · Smallholder agriculture · Nepal

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1 Introduction

Smallholder agriculture, often characterised by farm sizes < 2 ha, accounts for one-third of total global food production (Ricciardi et al. 2018), and also contributes around two-thirds of the food supply in developing countries (FAO 2017; Samberg et al. 2016). Smallholder food production is pivotal for food security in developing countries, especially in Asia and Africa, where smallholder agriculture is the dominant mode of production (Samberg et al. 2016). Successful achievement of Sustainable Development Goal (SDG) 2 *Zero Hunger* is crucial to sustaining life and secure livelihoods in the regions of smallholder dominance (Brown et al. 2019). Smallholder agriculture is practised in socio-ecological systems where farming continues amidst unfavourable socioeconomic, political, and environmental uncertainties (Clay and King 2019; Phuong et al. 2018). Aggravated climatic changes and variabilities challenge food security of smallholder systems (Eissler et al. 2019; Hussain et al. 2019). While adaptation in smallholder agriculture is imperative in the context of climatic variability; vulnerability, adaptive capacity, and resilience vary across agroecosystems (Aryal et al. 2020; Brown et al. 2019; Lamichhane et al. 2020). Though the vulnerability and adaptation of smallholder agriculture to climatic variability are well understood (Karki et al. 2020; Lamichhane et al. 2020; Morton 2007; Wood et al. 2014), the barriers to climate change adaptation and their influence on the choice of adaptation measures are not, especially in socioeconomically and environmentally heterogeneous agroecosystems. Insight into the barriers to adaptation and their determinants is essential for addressing impediments and guiding adaptation policy pathways to promote resilient smallholder agriculture.

Climatic variability impacts different crops in different ways, but most impacts have been shown to be negative (Asseng et al. 2011; Krishnan et al. 2011; Tiwari and Yadav 2019). Climatic variability and change have contributed to the reduction in yields of major cereal crops in regions of smallholder dominance like South Asia (Aryal et al. 2020; Khatri-Chhetri and Aggarwal 2017; Lal 2011). Although adaptive agronomic decisions (e.g. changing crop management) can contribute towards lowering the yield gap (Bryan et al. 2014), such practices must be adapted to diverse socioeconomic context of smallholder systems (Khanal and Wilson 2019). While regions of smallholder dominance show an increasing trend of rising temperature and variability in precipitation patterns (Krishnan et al. 2019), significant uncertainties remain with respect to the frequency, magnitude, and location of climatic impacts (Krishnan et al. 2019; Lal 2011). Sustaining smallholder agriculture in developing countries demands dynamic and adaptive options to cope with climatic and non-climatic stressors (Mishra et al. 2019; Morton 2007). In smallholder systems characterised by micro-climatic and socio-ecological heterogeneity, adoption of contextually-suited adaptation measures are necessary to sustain and increase agricultural production (Aryal et al. 2020).

Adaptation is a continuous and evolving process to cope with climatic impacts (Adger et al. 2009; Walker 2019). Significant climatic perturbations require sustained adaptation measures geared towards abating the impacts (Howden et al. 2007). Zilberman et al. (2012) defined adaptation as a set of strategies for responding to major environmental changes—current and future—that have the potential for significant and long-term consequences. In smallholder systems, adaptation is the outcome of the complex interplay of capacities and vulnerabilities within broader socio-ecological contexts (Jones and Boyd 2011). Choice of adaptation measures involve adoption decisions (Zilberman et al. 2012) guided by the broader adaptation strategy. Therefore, the adoption of adaptation measures by individual farmers is central to overall adaptation success in smallholder settings. Adoption is a multi-stage process where farmers implement adaptation measures to varying degrees in order to maximise the benefits (Adesina and Zinnah 1993). In smallholder agriculture, where multiple choices exist, farmers often adopt multiple adaptation measures to satisfy the specific adaptation need (Islam et al. 2014; Tessema et al. 2013). While composite indices have been created to describe the scale and extent of adoption of alternative adaptation measures (e.g. Zilberman et al. 2012), attempts to quantify the extent of adoption in smallholder agriculture are scant (e.g. Khanal and Wilson 2019). This has limited the ability to comprehensively understand climate change adaptation decisions by smallholder farmers (Dang et al. 2014).

Barriers are defined as the contextually constructed obstacles that may be overcome with necessary adjustments (Moser and Ekstrom 2010). Barriers to adoption of climate change adaptation measures have mostly been the topic of qualitative discourse (Adger et al. 2009; Azhoni et al. 2017; Chanza 2018; Islam et al. 2014; Jones and Boyd 2011). Moser and Ekstrom (2010) argue that barriers arise from the dynamic interplay of actors, context, and system of concern. Jones and Boyd (2011), in exploring social barriers to adaptation in western Nepal, defined social barriers in cognitive, normative, and institutional dimensions. In their study of the farming community in Bangladesh, Islam et al. (2014) depicted barriers in terms of natural, technological, social, economic, and institutional processes that were mostly interrelated and collectively influenced adaptation decisions. Islam et al. (2014) also posited that barriers are dictated by the lack of endowment of financial, built, human, social, and natural capital. Understanding adaptation barriers could inform ways to offset climatic risks, identify appropriate adaptation measures, and guide policies that contribute to successful adaptation (Azhoni et al. 2017; Esham and Garforth 2013; O’Brien et al. 2006). However, attempts to quantify barriers to adaptation have been limited (e.g. Wang et al. 2020) despite the urgent need to comprehensively inform adaptation policy in smallholder agriculture in developing countries.

In this study, we empirically quantified the adoption of climate change adaptation measures in smallholder agriculture, in addition to barriers to adoption and their determinants, across three agroecosystems (Mountain, Hill, Terai) in the Far Western Province, Nepal. We derived composite adoption indices for crop adjustment, farm management, fertiliser management, and non-farm adjustment and off-farm adjustment. Additionally, we derived barrier indices aligned with the capital-based framework for social, technological, environmental, economic, and institutional dimensions. We then correlated the derived indices to explore the potential influence of barriers on adoption of climate change adaptation measures across agroecosystems in the study area. We also used multiple regression to identify the determinants of adaptation barriers. Finally, we discuss the policy implications of the results for promoting adaptation in smallholder agriculture. Our findings can inform agricultural development policies and adaptation plans both at local and regional levels.

2 Methods

2.1 Study area

The study area encompasses nine districts in the Far Western Province (Fig. 1a) of Nepal, with a total population of almost 2.5 million people (CBS 2016). Agriculture is the mainstay of the Nepalese economy as it contributes about one-third of the national gross

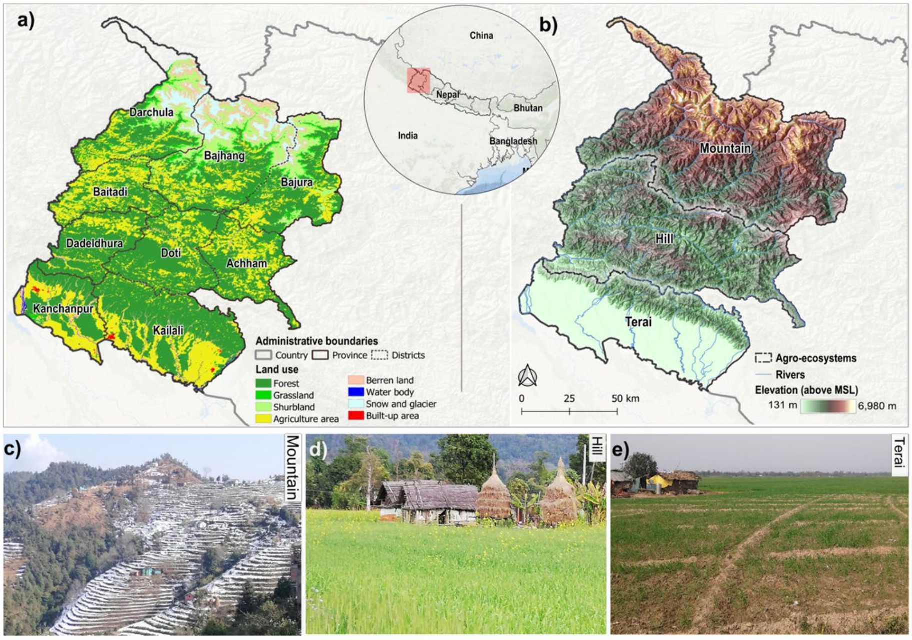
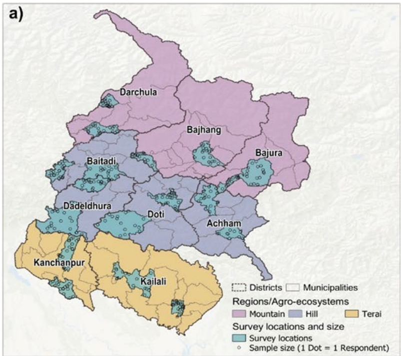


Fig. 1 Study area physiography. **a**) Agriculture is the second largest land use in the study area (ICIMOD 2013), **b**) study area is eco-physiologically heterogeneous that encompasses Mountain, Hill, and Terai agroecosystems, **c**) the Mountain agroecosystem is the high altitude cold region with steep topography, **d**) the Hill agroecosystem, characterised by sub-tropical to temperate climate, transitions Mountain and Terai with numerous flat, low-lying river terraces, and **e**) the Terai agroecosystem consists of fertile plains with tropical to sub-tropical climate

domestic product and employs around two-thirds of the economically active population (CIAT et al. 2017). Agriculture in the country is predominantly practised in fragmented small-size farms < 1 ha (CBS 2013). Despite the increase in non-farm options for income generation in recent years, livelihoods are primarily based on smallholder agriculture for the large majority of the population (CIAT et al. 2017).

The study area is the poorest region of Nepal (Zhang et al. 2018). The province spans three major agroecosystems—Mountain, Hill, and Terai. The Mountain agroecosystem, situated above 2,000 m above sea level, is characterised by a cold climate, high-altitude, and steep landforms (Fig. 1b, c) that make up the northern part of the study area. Most of the districts in the agroecosystem are chronically food insecure (NeKSAP 2014). The Hill agroecosystem encompasses an elevation range of 300–2,000 m above sea level and is characterised by sub-tropical to temperate climate zones (Fig. 1b, d). In the Mountain and Hill agroecosystems, crops are grown both in upland rain-fed terraces and low-lying irrigated fields in river basins, but the Mountain agroecosystem encompasses fewer and smaller low-lying irrigated fields. The Terai, the southernmost agroecosystem with elevation < 300 m, is a plain with fertile soil spanning the tropical to subtropical climatic zones (Fig. 1b, e). Farms in the Terai are suited to a variety of crops with the region regarded as the country's food basket (MoAD 2016). Crop and livestock are mostly integrated with all agroecosystems, which is the characteristic feature of Nepalese smallholder agriculture (CIAT et al. 2017).



b)

Attributes of respondents		Percentage
Gender	Male Female	71 % 29 %
Age	< 35yrs 35 –65yrs > 65yrs	23 % 56 % 21 %
Education	No education Primary education/literate Secondary education Tertiary education	16 % 45 % 25 % 11 %
Agriculture experience	< 10yrs > 10yrs	6 % 94 %
Agro-ecosystems/Regions	Mountain Hill Terai	30 % 45 % 25 %

Fig. 2 Survey locations and the respondent attributes: **a**) Respondents were drawn from two municipalities of each district in the study area; and **b**) survey respondents exhibited varying socio-demographic attributes

Rice, wheat, and maize are the major cereal crops produced in the study area and production is mostly used for domestic consumption. Examination of meteorological data (1990–2010) exhibits change and variability in climatic conditions for crop growing seasons across all agroecosystems. Growing season maximum temperature increased at a faster rate in wheat and maize growing seasons for the Mountain and Hill agroecosystems, but increased more slowly for the rice-growing season (Supplementary Information 1). Rainfall shows an overall decreasing trend, but variability in growing season rainfall is evident. Rice and maize growing seasons show the highest variability in rainfall. Variability in rainfall is highest in the Mountain agroecosystem. Irrigation coverage in the study area is around 60% (CBS 2013), mostly implemented via small-medium-sized irrigation systems that are vulnerable to climatic variability (Parajuli 2017). The province is likely to suffer more frequent and prolonged drought and more erratic rainfall in the future (see Karmacharya et al. 2007; Khatiwada et al. 2016; Wijngaard et al. 2017). In addition, Lamichhane et al. (2020) observed a low–moderate resilience of smallholder agroecosystems in maintaining their crop yields given climatic variability. Increases in climatic variability and extremity in smallholder systems with weak resilience are likely to impact crop production in future.

2.2 Data collection

We conducted face-to-face interviews with a total of 327 smallholder farmers in the Far Western Province, Nepal. We used a stratified random sampling approach to recruit respondents for the interview. Given the environmental and socioeconomic heterogeneity in the study area, survey locations were allocated across all districts in the study area (Fig. 2a). We randomly selected two municipalities from each district, and then a ward from the selected municipalities was randomly identified for farmer interviews. Our approach of stratified multi-stage random recruitment of respondents better represents the heterogeneous study area (see Bansal 2017; Fowler 2009). We acquired the list of residents from ward offices. We then randomly selected potential interviewees from the selected wards that satisfy the recruitment criteria. Along with a willingness to participate, farmers must have had at least 5 years of farming experience and be aged > 18 years to be eligible for the survey.

Farmers were asked about their adoption of climate change adaptation measures and the barriers experienced. Responses were registered using a 1–5 Likert ranking (Supplementary Information 2). We recorded farmers' adoption of 25 individual adaptation measures falling under the broad headings of crop adjustment, farm management, fertiliser management, non-farm adjustment, and off-farm adjustment. Adaptation measures were identified through the literature (e.g. Devkota et al. 2017; Khanal and Wilson 2019) and their relevance was confirmed for the study area in a questionnaire pre-test. A similar approach was used to capture the influence of 25 barriers falling under the broad headings of social, techno-informational, economic, environmental, and institutional. Farmers were further encouraged to express their views qualitatively regarding adaptation and barriers as open-ended comments. The questionnaire also included a section entailing broader socio-ecological (e.g. education, farm size, and credit access) information and perceptions (e.g. belief in climate change). Lamichhane et al. (2021) comprehensively present the data and the data collection methodology used in this research. Trained interviewers conducted interviews in the Nepali language after pre-testing of the questionnaire with farmers. Approval for fieldwork was acquired from the Human Research Ethics Committee at Deakin University. The Mountain, Hill, and Terai agroecosystems represented 30%, 45%, and 25% of the respondents, respectively.

2.3 Derivation of indices

Adoption indices were derived based on farmers' adoption of adaptation measures. We built upon the approach from Below et al. (2012) where adaptation an activity-based adoption index was calculated as the sum of weighted adaptation measures of farmers/households as follows:

$$AAI_j = \sum\nolimits_1^n p_{ij} \cdot w_i \tag{1}$$

where p_{ij} is the uptake of adaptation measure i by household j (1 if practiced, otherwise 0) and w_i is the weight assigned to the measure i through focus group discussion. However, in complex smallholder systems, adoption of adaptation measures cannot be characterised as dichotomous decisions. Instead, farmers tend to adopt measures to varying degrees to maximise benefits and manage risk (Adesina and Zinnah 1993). Sidibé (2005) posits that the extent of adoption reflects the weight that the farmers assign cognitively to the respective adaptation measures for the given socio-ecological context. Aligning with this proposition, we leveraged the methodological complexity by capturing farmers' ranking of the extent of adoption in the five-point Likert scale. We modified Eq. (1) to quantify the adoption indices for smallholder households, normalised by the number and weight of the responses following Wedawatta et al. (2014):

$$AI_h = \sum_{i=1}^{N} \frac{a_{ih} \cdot w_{ih}}{N \cdot \max(w_{ih})} \tag{2}$$

where AI_h is adoption index for household h; a_{ih} is the value for adoption of adaptation measure (1 if adopted, otherwise 0); w_{ih} is weight captured as the extent of adoption of adaptation measure i ranked by respondent h; $\max(w_{ih})$ is maximum assignable rank weight to adaptation measure i, and N is the number of adaptation measures considered. We employed Eq. (2) in deriving overall adoption indices, and the adoption indices for five main types of adaptation in smallholder systems: crop adjustment, farm management, fertiliser management, non-farm adjustment, and off-farm adjustment.

Relevant works that empirically derive barrier indices are scant. Wang et al. (2020) empirically quantified barriers accounting for the deviation of farmers' response from the ideal situation. Here, we posit that adaptation to climate change is determined by farmers' cognitive evaluation of barriers based on their perceived risk and capacities for a given socio-ecological context (see Masud et al. 2017; Shaffril et al. 2020). We adapted Eq. (2) to calculate barrier indices as:

$$BI_h = \sum_{j=1}^{N} \frac{b_{jh} \cdot w_{jh}}{N \cdot \max(w_{jh})} \tag{3}$$

where BI_h is adoption barrier index for household h; b_{jh} is value for barrier (1 if exists, otherwise 0); w_{jh} is the weight represented as the extent of barrier j assigned by respondent h; w_{max} is maximum assignable rank weight to barrier j, and N is the number of barriers considered. Indices were derived for social, environmental, techno-informational, economic, institutional, and environmental barriers.

Since the indices were normalised, they retain their value between 0 and 1 where the higher value signifies a greater barrier to the adoption of adaptation measures. Additionally, we carried out a pairwise comparison of indices across agroecosystems to see if the variations were significant.

We assessed the degree of correlation between barrier indices and adoption indices to examine if barriers can explain variability in the adoption of adaptation measures using Spearman's rank correlation test. We used barrier indices derived for social, environmental, techno-informational, economic, governance, and environmental dimensions as they capture the variability in the adoption of adaptation measures. These barriers were correlated with the adoption indices derived for crop management, farm management, fertiliser management, non-farm adjustment, and off-farm adjustment. The correlation analysis allowed us to explain the strength and the direction of influence for the adoption of adaptation measures in composite terms.

2.4 Determinants of barriers to adaptation

Barriers to adoption of adaptation measures are implicit in smallholder systems. We posit that the individual, socioeconomic, environmental, and institutional capitals in smallholder systems influence the barriers to adoption of adaptation measures. We used a set of predictor variables, based on a literature review, to regress against the overall barrier indices. A simple linear regression, as used by Khanal and Wilson (2019), was employed with the barrier indices as the single dependent variable predicted by a set of capital-based variables relevant to smallholder systems (Table 1). The predictor variables comprise dummy, continuous, and scaled variables. We converted predictor variables with dichotomous responses (e.g. gender) to dummy variables (see Amare and Simane 2017), and treated the scaled variable as a continuous variable (Harpe 2015). We calculated the variance inflation factor (VIF) to detect multicollinearity among predictor variables (Fox 2016). Our regression model, with 18 predictors with 315 observations, satisfies generally recommended sample size requirements (i.e. number of observations > 10 × predictor variables) for regression analysis (see Jenkins and Quintana-Ascencio 2020; Wilson Van Voorhis and

Table 1 Determinants of adaptation barriers (variable description and measurements)

Variable	Definition	Justification for use	Citations	Measurement
Household head	Gender of the household head	Gender-based inequalities and exclusions are common in the study area. Male headed household are then more likely to access resources and harness opportunities to reduce barriers than the household headed by the female member	1, 6, 8	Dummy: 1 if male heads the household, 0 otherwise
Household size	Number of family members in a household	Larger family size means the easy availability of household workforce for agriculture, and so fewer barriers to practice adaptation	1, 3	Categorical/scale: 1 if family size ≤ 3, 2 if 4–6, 3 if ≥ 7
Education	Highest level of education of the family member dwelling in the household	Smallholders with educated members are more likely to overcome the adaptation barriers since they can access and exploit opportunities and resources	1, 2, 3, 4, 5, 6	Categorical/scale: 1 if illiterate, 2 if primary education, 3 if secondary education, and 4 if tertiary education)
Trainings attended	Farmer's attendance in training in topics related to agriculture and climate change	Farmers that attend/exploit training opportunities are likely to have a better understanding of climatic risk and adaptation measures, and are driven to offset adaptation barriers	7, 6	Dummy: 1 if farmer has attended trainings, 0 otherwise
Farm size	Size of the land held by the farmer in smallholder system	Farmers with larger farm size are more likely to invest in adaptation and remove the adaptation barriers	1, 3, 6	Categorical/scale: 1 if farm size < 0.5 ha, 2 if 0.5–1 ha, 3 if 1–1.5 ha, 4 if 1.5–2 ha, 5 if > 2 ha)
Crop diversification	Number of major crops grown in the farm	Crop diversification indicates the suitability of land for multiple crops or the use of land for appropriate crops. A higher value of crop diversification infers a lower importance of barriers to adopt adaptation measures. Farmers that diversify the crops are more adaptive and experience a lower level of barriers to adaptation	9	Continuous (number of major crops reported by the farmers)

Table 1 (continued)

Variable	Definition	Justification for use	Citations	Measurement
Extension services	Agricultural service providers operating at the local level	Farmers that can access extension services are more likely to find ways of alleviating adaptation barriers through increased exposure to opportunities and incentives	1, 3, 5, 8	Dummy: 1 if extension services are locally available, 0 otherwise
Land tenure	The ownership of the farm that the farmer runs smallholder agriculture in	Farmers running smallholder agriculture in their own land are likely to invest in adaptation measures to alleviate the barriers	1, 6	Dummy: 1 if the farmers own the land under cultivation, 0 otherwise
Farmers' group membership	Household (or family member) is a member of the farmer's group	Engagement with community-based organisations (CBOs), like farmers' groups, opens up opportunities to remove barriers through experience sharing or collective decision making	1, 3, 8	Dummy: 1 if farmer is the member of farmers group, 0 otherwise
Farming practice	Labour dependency for farming	With the increasing trend of youth out-migration, the farmers with labour-intensive agricultural practice experience a higher degree of barriers to adaptation	10	Dummy: 1 if farming practice is labour dependent, 0 otherwise
Credit access	Household (or family member) has affiliations with cooperative groups	Cooperative members have easy access to credit. Easy access to credit enables farmers to invest in the removal of adaptation barriers	2, 3, 6	Dummy: 1 if the farmers' household holds cooperative membership, 0 otherwise
Non-farm income	Engagement of family members in non-farm income	Higher engagement in non-farm income implies either a retreat of reliance on agriculture or repulsion of the farmer from agriculture, which might have been triggered by adaptation barriers	2, 3, 6	Continuous (number of household members > 18 years engaged in non-farm income)

Table 1 (continued)

Variable	Definition	Justification for use	Citations	Measurement
Reliance on external inputs	Farmer's dependency on an external supply of seeds, fertilisers and pesticides	Farmers with dependency on external inputs are likely to report high adaptation barriers given market uncertainty on the timely availability of external inputs	11	Dummy: 1 if the farmer is dependent on external inputs, 0 otherwise
Market distance	Distance to a nearby market to buy inputs and/or sell farm produce	Closer market distance signifies lower barriers in terms of access to farm inputs (e.g. fertiliser) and sell produces (e.g. grains and vegetables)	1, 3	Continuous variable
Monsoon dependency	Farmer's reliance on monsoon for farming	Monsoon onset and retreat are becoming increasingly uncertain and act as a barrier to the adoption of adaptation measures otherwise possible	2,12	Dummy: 1 if agriculture is dependent on monsoon, 0 otherwise
Weather information	Access to the weekly weather forecast to guide farm practices	Better informed farmers are hypothesised to be able to make informed adaptation decisions and alleviate the barriers	1, 2, 3, 6	Dummy: 1 if the farmer can access weekly weather information, 0 otherwise
Climate belief	Degrees of belief on the fact that the climate change is happening	Belief in climate change drives farmers to adapt to climate change. Such farmers seek avenues to the successful implementation of adaptation measures and are likely to report lower degrees of adaptation barriers	3	Continuous/scale: 1 (no belief on climate change) to 5 (strong belief on climate change)
Risk experience	Farmers' experiencing a detrimental climatic impact on smallholder agriculture	Farmers that experienced climatic risk tend to develop skills and explore options to depreciate adaptation barriers	1, 3, 5, 8	Dummy: 1 if farmer experienced climatic risk, 0 otherwise

1 = Below et al. (2012), 2 = Deressa et al. (2009), 3 = Khanal and Wilson (2019), 4 = Maniruzzaman et al. (2015), 5 = Stefanovic et al. (2019), 6 = Thinda et al. (2020), 7 = Danso-Abbeam and Baiyegunhi (2017), 8 = Zamasiya et al. (2017), 9 = Belay et al. (2017), 10 = Harvey et al. (2018), 11 = Zilberman et al. (2012), 12 = Ozor et al. (2010)

Morgan 2007). Variance inflation factors (VIF) for the predictor variables were < 5 indicating no multicollinearity between independent variables.

Given varying degrees of smallholder agriculture resilience across agroecosystems (Lamichhane et al. 2020), we hypothesise that the determinants of barriers vary across those agroecosystems. Having insufficient observations to run regression models for each agroecosystem with all the predictor variables in Table 1, we used stepwise regression to identify the best-performing models with differing number of predictor variables (Shinbrot et al. 2019; Wubetie 2019), and then used a k-fold cross-validation approach to identify the model with lowest prediction error (see Kuang et al. 2019; van Etten et al. 2019). We divided the data into 10 subsets (k) where one of the subsets was used as the test set (20% of the observations) and the rest as the training sets (with 80% of the observations). Cross-validation error was computed as the model prediction error (RMSE). The model that generated lowest cross-validation error was selected as the most suitable model to predict the determinants of barriers in the Mountain, Hill, and Terai agroecosystems. The R functions *regsubsets* (*leaps* package (Lumley 2020)) and *train* (*caret* package (Kuhn et al. 2020)) were used for selecting regression models and identifying the model with the lowest prediction error, respectively.

3 Results

3.1 Adoption of climate change adaptation and barriers to adoption

Results indicate that smallholder farmers adopted crop adjustment and fertiliser management adaptation measures to a greater extent than non-farm adjustment and off-farm adjustment (Fig. 3a). For crop adjustment, change in crop variety and the selection of higher-yielding varieties were the most common adaptation measures. Only a small cohort of farmers reported extensive adoption of adaptation measures related to farm management. In contrast, more than a quarter of respondents reported no adoption of farm-management measures. Adjustment in manure application was a more widely practised adaptation measure than adjustment in the application of chemical fertilisers. Adjustment in livestock population was the most practised non-crop adaptation measure. Farmers reported a lower uptake of off-farm adjustment to cope with climate change impacts.

The majority of farmers reported a higher degree of barriers in most economic and techno-informational dimensions (Fig. 3b). Smallholder farmers rated social barriers lower except for the collective decisions for adaptation. Uncertainty of weather patterns, limited availability of water for irrigation, and limited land capability for alternative farm management were the most common environmental barriers identified. Access to crop insurance (and subsidies) and market access were the highest rated governance and institutional barriers.

3.2 Indices of adoption and barriers

3.2.1 Adoption indices

Variation in adoption indices was observed across agroecosystems (Fig. 4, Supplementary Information 3). The Terai region exhibited the highest mean adoption index (0.4) value for crop adjustment with the lowest variability in adoption among farmers (SD = 0.09).

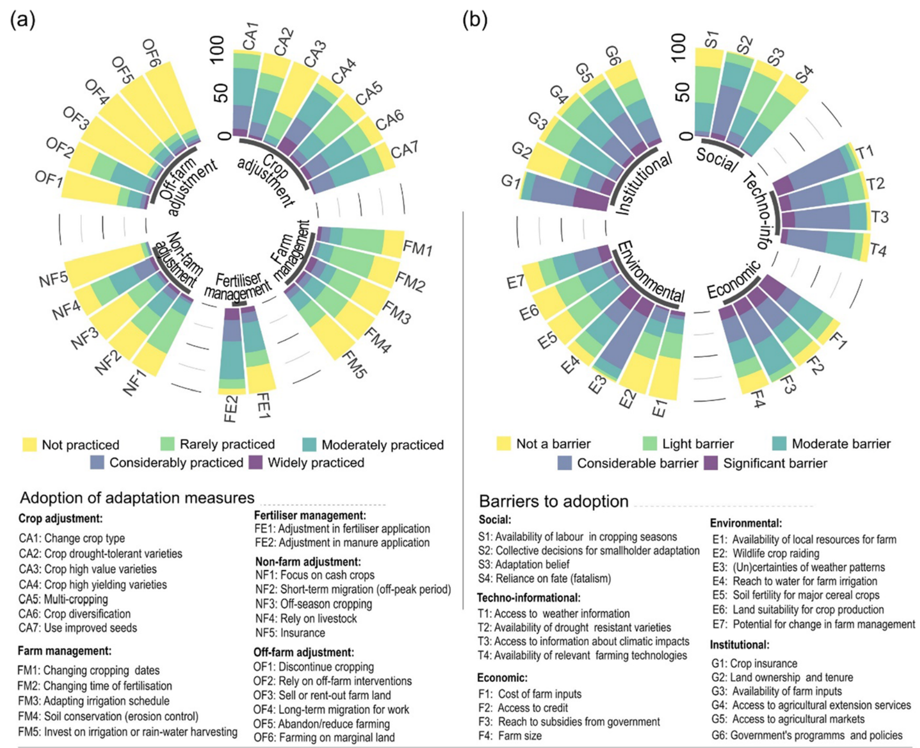


Fig. 3 Farmers' responses to adoption and barriers: **a**) Adoption rate of adaptation measures (%), and **b**) barriers perceived by smallholder farmers (%). Adaptation measures related to crop adjustment and fertiliser management were reported to be more highly practiced than the measures associated with off-farm adjustment, non-farm adjustment, and farm management measures. Farmers rated the techno-informational and economic barriers to adaptation highly

The Hill agroecosystem displayed the highest mean adoption index for farm management, while the Terai showed the lowest. The adoption index for the Hill agroecosystem was the largest for fertiliser management. Off-farm adjustment for all agroecosystems was low (<0.3) and agroecosystems exhibited mostly non-significant differences. Non-farm adjustment was highest for the Hill agroecosystem, followed by the Mountain and Terai. Overall, the Hill agroecosystem exhibited the highest mean adoption indices, with Terai lowest.

3.3 Barrier indices

Smallholder agriculture across agroecosystems exhibited varying levels of adaptation barriers (Fig. 5, Supplementary Information 4). The mean value for social barrier indices was lowest for the Hill agroecosystem and highest for the Mountain. The techno-informational barrier was lowest for the Terai and highest for the Mountain. The economic barrier was highest in the Terai, while such barrier indices were relatively lower for the Mountain and Hill agroecosystems, and the variation was non-significant between them. The Environmental barrier was significantly higher in the Terai region, while it was lower for the Hill and Mountain with a non-significant difference. In terms of governance and environmental barriers, the variations were non-significant between the Hill and Mountain

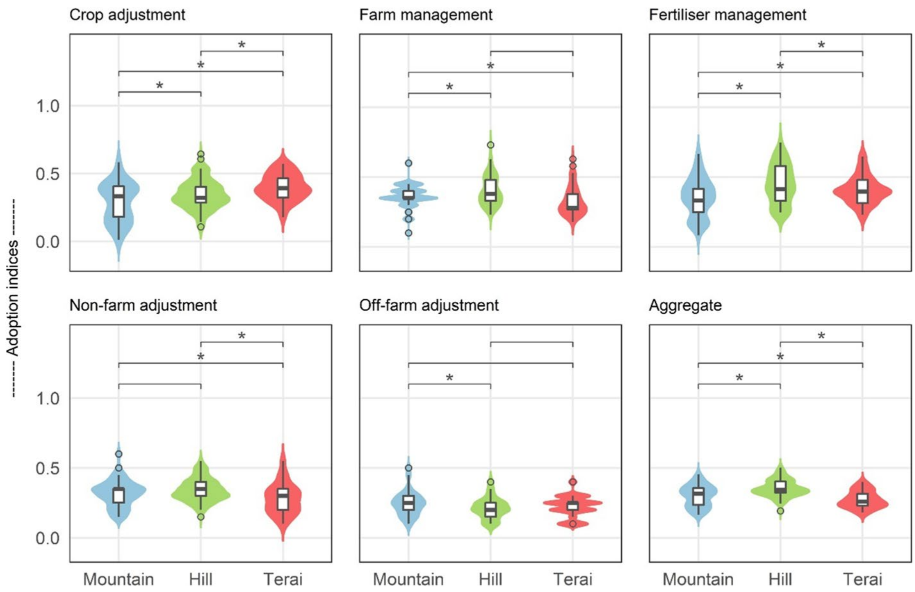


Fig. 4 Adaptation indices derived for various adaptation strategies for the Mountain, Hill, and Terai agroecosystems. Adaptation indices often varied significantly across agroecosystems at the significance level of 0.05 (*)

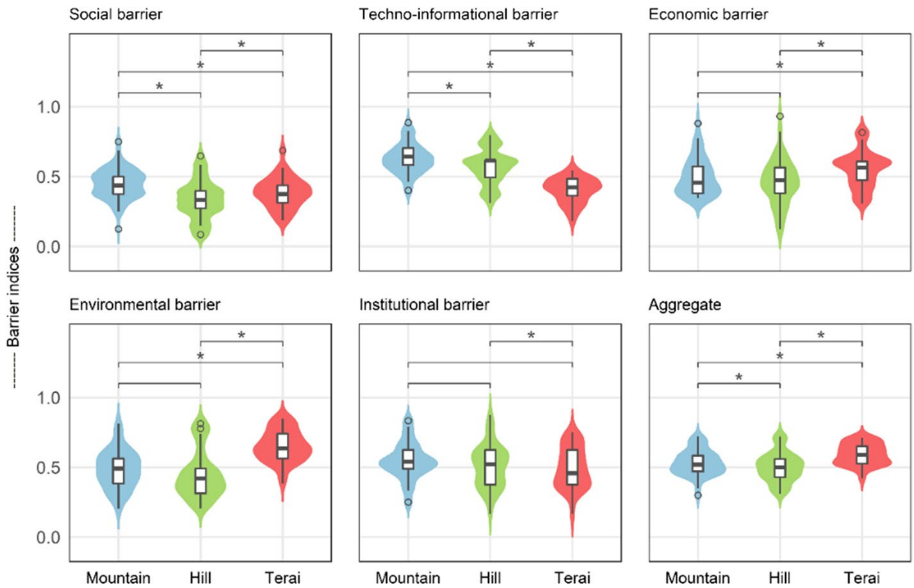


Fig. 5 Variability in barriers indices was observed across barrier-domains and the agroecosystems. The Hill and Terai agroecosystems respectively exhibited the lowest and highest level of adaptation barriers. Barrier indices often varied significantly across agroecosystems at the significance level of 0.05 (*)

agroecosystems. Overall, the Terai agroecosystem exhibited the highest barrier indices, while the variability of the barrier indices tended to be higher in the Hill and Mountain agroecosystems.

3.4 Relationship between barriers and adoption

Correlation results suggested a varied relationship between adoption and barrier indices (Fig. 6). Adoption of climate change adaptation measures for crop adjustment was inversely related to the institutional barriers. Social, economic, and environmental barriers exhibited a significant and inverse relationship with the adoption in farm management operations in smallholder agriculture. Fertilisation management exhibited a non-significant and weak relationship with barriers except the techno-informational barrier. Off-farm adjustment—the adoption of the maladaptive choices—showed a positive relationship with the identified barriers but was significantly correlated only with economic, technological, and institutional barriers. Non-farm adjustment exhibited a significant and inverse relationship with social, economic, and environmental barriers. Variability in the relationship between adoption and barriers was observed across the Mountain, Hill, and Terai agroecosystems (Supplementary Information 5). The Hill agroecosystem mostly exhibited a weak and non-significant relationship between barriers and adoption, whereas the relationship was mostly significant and stronger in the Mountain and Terai.

3.5 Determinants of barriers

Our regression model yielded R-squared and Adjusted R-squared values of 0.64 and 0.62, respectively, indicating a good model fit for social science research (Fig. 7, Supplementary

Fig. 6 Correlation between adoption and barrier indices for the study area. Significant correlation coefficients are shown in bold at 0.05

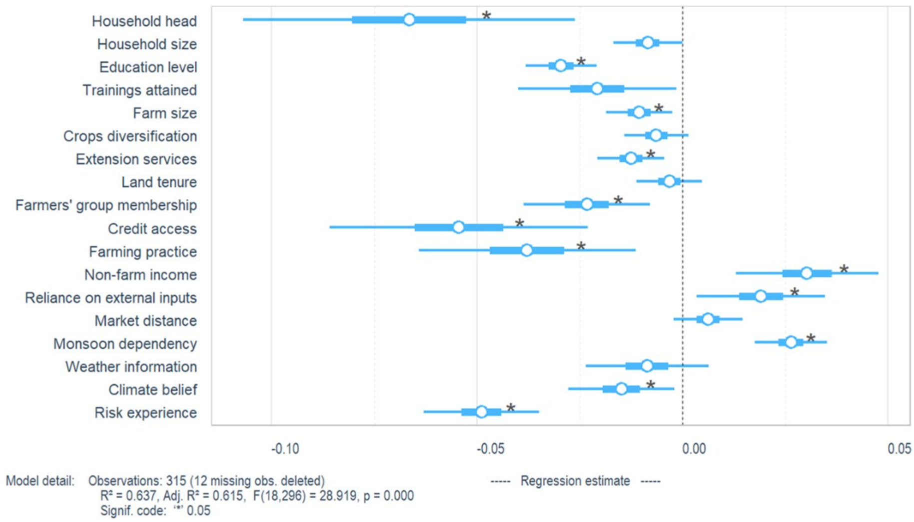


Fig. 7 Regression summaries: estimates, significance, and the confidence interval of the predictor variables of adaptation barriers. The majority of the predictor variables exhibited significance at 0.05 (*)

Information 6). Most variables were significant predictors ($p < 0.05$). Explaining the highest variance in adaptation barrier included gender of household head, credit access, farming practice, and climatic risk experience, and these were inversely related to the adaptation barriers. Variables with a positive relationship to barriers included dependency on external inputs, reliance on monsoon rain, non-farm income, and distance to market. Variables like household size, farm size, land tenure, and market distance showed not significant relationship with barriers. The predictors of barriers varied between agroecosystems (Supplementary Information 7). The gender of the household head being male and credit access was inversely related to barriers to uptake of adaptation measures in smallholder agriculture for all agroecosystems. Education, crop diversification, extension services, land tenure, affiliation with farmers' groups, dependency on external inputs, market distance, and the risk experience showed the strongest relationships with barriers over different agroecosystems in the study area.

4 Discussion

4.1 Adoption of adaptation measures and barriers to adoption

We assessed the adoption of climate change adaptation measures, and barriers to adoption and their determinants, in smallholder agriculture based on a survey of 327 farmers in the Far Western Province of Nepal. Our findings highlight the significant variability in adoption of adaptation measures and barriers across agroecosystems. The most common adaptation measures included crop adjustment, farm management, and fertiliser management. In terms of barriers, techno-informational, environmental, and economic barriers were most commonly reported, with some variation across agroecosystems. The Terai, known as Nepal's food basket, showed the highest overall level of adaptation barriers. The findings are consistent with previous studies (e.g. Lamichhane et al. (2020)) where the lowest degree of resilience in smallholder food production was reported for the Terai. Higher standard deviation in adoption and barrier indices were observed mostly for the Hill and Mountain indicating considerable variability.

Uptake of crop adjustment and fertiliser management choices in smallholder agriculture are primarily the farmers' independent decisions (Mugwe et al. 2009). Corral et al. (2020) found in a Mexican study that farmers with autonomy in decision-making showed substantially greater persistence in adaptation. Autonomy in crop adjustment allowed farmers to identify not only the best performing crop variety for the local agroecosystem (MoAD 2018) but also reduced the risk associated with the introduction of new varieties (Adhikari 2016). Since smallholder food production is primarily for subsistence (Adhikari 2016), farmers engage in risk averse adaptation measures to prevent severe food-deficiency. A farmer in the Terai (R1) reported autonomy in selection of crop variety, piloting, and large-scale adoption as an adaptation strategy to avert potential climate risks. A Hill farmer—growing both new and local varieties as the adaptive strategy—stated that the new variety comes with opportunities and risk and added that the continuation of locally cultivated variety would hedge against any potential production losses (R2). These statements indicate that adoption of adaptation measures is a complex and dynamic process where farmers analyse the trade-offs of available options within the local socio-ecological context.

> R1: ...... I've been replacing the seeds over the years. You know, the yield declines if I don't. So, I normally buy a small amount of seed and then increase its amount in the first year. In subsequent years, I grow the same variety at different scales depending its first year's performance. I replace that variety only after 3-4 years, and repeat this approach. Otherwise, there would be more pest attacks and yield decline.....
> R2: ...the new varieties produce good yield, but require good care. If things go wrong you are less likely even to get seed return...

We observed a higher level of social barriers in the Mountain and Terai agroecosystems and these had a significant inverse relationship with crop adjustment. This finding aligns with Jones and Boyd (2011) who found that a restrictive social environment constrained adaptation in western Nepal. To illustrate their impact, a farmer in the Terai (R3) reported that a lack of collective decisions often discourages the adoption of adaptation practices in smallholder agriculture:

> R3 …I cropped Sukkah-3[1] last year. My field does not have road access, so I have to go through other's fields. Farmers of those fields planted other varieties. Though the crop in my field was ready to harvest, I could not access my field as the crop in others field was not harvested. They planted different variety. I had a big harvest loss. It's not encouraging at all to grow recommended varieties, is it? …

Correlation analysis mostly showed a significant inverse relationship between farm management and both economic and environmental barriers for all agroecosystems. Irrigation using groundwater by operating pump-sets (a common irrigation practice in the Terai) was expensive for smallholder farmers (see Shrestha and Dahal 2019). Fragile soils, difficult terrain, and microclimatic variability associated with Mountain regions (Jodha 2007) were among the most common environmental barriers impeding adjustments in farm management.

[1] Sukkha-3 is a drought-tolerant rice variety recommended by the Nepalese government for the Terai region.

Smallholder farmers in the Hill agroecosystem employed adjustments in fertiliser management more often than farmers in the other agroecosystems. Mountain farmers reported heavy reliance on manure as fertilisation despite the decrease in livestock population in recent years (MoLD 2017). Seasonal environmental variability was also reported to be restrictive for adjustment in fertiliser management in the Mountain agroecosystem. A farmer in a Mountain district reported that (R4): "…fertilisation of rice delays the ripening and can delay harvest time until the cold season" which results in lower grain filling due to the cold temperatures. During the fieldwork for this study, we observed farmers applying manure to wheat within a month of seeding without incorporating it into the soil which can lead to high nutrient loss (Supplementary Information 8). Conventional manure application practices and limited access to information for manure/fertiliser scheduling were reported by farmers in the Mountain agroecosystem. In contrast, farmers in the Terai reported greater reliance on chemical fertilisers. Uncertainty about the timely availability of chemical fertilisers was extensively reported. In addition, we observed a significant inverse relationship between fertiliser management and economic and the institutional barriers in the Terai. Hill farmers reported the complimentary use of manure and chemical fertilisers: R5 "…We used to use only cattle manure, but since we reduced the number of cattle, we have now started applying a small amount of chemical fertiliser, mainly urea…". The capacity of Hill farmers to exploit alternative forms of fertilisation is likely to have helped offset the barriers to fertiliser management.

Terai famers more often adopted non-farm adjustment as climate change adaptation measures. Deressa et al. (2009) reported a higher level of uptake of non-farm adjustments near cities. Smallholder farmers' proximity to larger cities and market centres in the Terai might have motivated them to adopt non-farm adjustment measures, while the higher economic and environmental barriers in the Mountain might have contributed to the lower uptake of non-farm adaptation measures. Indices on off-farm adjustment were low with mostly non-significant differences across agroecosystems. Off-farm adjustment was significantly related to techno-informational and economic barriers in the Hill agroecosystem, while being related to environmental barriers in the Mountain.

4.2 Determinants of adaptation barriers and policy implications

At the provincial level, our findings suggest that by removing gender-based disparities in agricultural operations, easing farmer's access to credit, changing farming practices, and capitalising on farmers' experience in successfully dealing with climatic risk could contribute to removing barriers to the adoption of specific climate change adaptation measures. These findings are consistent with previous work with smallholder farmers in developing country contexts (e.g. Alauddin and Sarker 2014; Jones and Boyd 2011; Khanal and Wilson 2019; Tambo and Abdoulaye 2012). However, findings for the whole Province can hide important variability across agroecosystems that exhibited significant differences in barriers. Gender of household head (being male) and credit access were the key predictors of barriers for all agroecosystems. Jones and Boyd (2011) observed restrictive opportunities and even institutional constraints to adaptation for females in western Nepal. Adaptation policies for smallholder systems must focus on removing gender-based discrimination and provide female-led smallholder households with improved access to opportunities. Access to credit was another key predictor exhibiting a strong negative coefficient with barriers for all regions. The finding is consistent with previous literature (e.g. Deressa et al. 2009; Khanal 2018) which found increased adaptation follows better access to credit in Ethiopian and

Nepalese smallholders. We observed that farmers with access to subsidised electricity to run tube-wells reported more frequent irrigation compared to farmers without such access. For regions with pervasive poverty, such as the study area, there is a strong need to ensure easy access to credit or subsidies to implement adaptation measures.

Education was the major predictor of barriers in agroecosystems with higher rates of illiteracy (i.e. Mountain and Hill) (CBS 2016). Education and training may remove some adaptation barriers as farmers may be better able to access information, services, and opportunities (Thinda et al. 2020). Extension services were significantly but negatively related to barriers, especially for the Hill and Terai as is consistent with the findings of Khanal and Wilson (2019). Issues with land tenure need to be carefully handled as the disparity in land ownership is high (Wily et al. 2008). A farmer in the Terai stated that the lack of interest in long-term adaptation measures was exacerbated by the absence of formal long-term land leasing contracts and entitlements (R6). Timely availability of inorganic fertiliser and seed remains of one of the greatest challenges in Nepalese smallholder agriculture (Henderson 2016). Limited market access, especially in the Hill and Mountain agroecosystems was related to a higher level of barriers and such distance could inhibit productivity increases (Pradhan et al. 2015). A stable supply chain would encourage remote smallholder farmers to adopt adaptation measures. Monsoon dependency was significantly related to the barriers in the Terai as farmers require costly tube-wells to irrigate their fields. Policies could aim to assist with the provisioning of pump-sets and subsidised electricity supply to farmers to alleviate such barriers.

> R6: Why should one invest in someone else's land in coping with climate impacts when there is no reassurance of being allocated the same land for cultivation in subsequent years?

Individual determinants of barriers often create restrictive conditions for collective adoption. Adaptation policies need to create a conducive environment for farmers to adopt adaptation measures by addressing the predictors holistically which include gender empowerment, easing credit access, education, training, extension, tenure, market connection, and reduce external dependencies.

4.3 Broader policy implications for climate change adaptation and food security

Climatic change impacts on subsistence agriculture in developing countries are likely to heighten food insecurity and generate cascading impacts in multiple fronts, including health, well-being, and livelihoods. The NAP identifies the following key gaps to climate change adaptation in agriculture in Nepal: a lack of climate-resilient crop varieties, limited access to climate information, extension services, inadequate means of adaptation, vulnerable irrigation systems, and poor governance mechanisms (MoPE 2017). Our findings on the barriers to adoption are generally consistent with these gaps, but the relevant predictors of barriers, e.g. credit access, market access, land tenure, and inputs availability, are not well accounted in NAP. Sectoral policies, e.g. Agriculture Development Strategy (ADS), also aim to improve farmers' climate resilience through the programs like promotion of stress-tolerant crop varieties, increasing farmers access to climate information and extension services, provisioning farmers' welfare fund and insurance (MoAD 2016).

Nepal has set an ambitious target to increase per capita food grain production by 60% by 2030 in its commitment to Sustainable Development Goal 2 (NPC 2017), and targets increasing total grain production by 40% by 2035 in ADS (MoAD 2016). Achievement of the production targets relies on the success of climate change adaptation, among others. Policy documents have identified and prioritised the adaptation measures but barely accounted for the barriers that may impede adaptation. Therefore, the scrutiny of adaptation barriers in smallholder agriculture directly contributes to the refinement of the adaptation programmes to eliminate such barriers. Findings directly contribute the local adaptation plans, e.g. Local Adaptation Plan of Action (LAPA), while it provides insight on the potential barriers that that national adaptation policies may endure. Significant differences in adoption and barriers across agroecosystems were observed, but the adaptation policies are not adapted to the heterogeneous agroecosystems. Our results suggest developing holistic adaptation policies that could address the intertwined determinants of barriers while tailoring strategies to individual agroecosystems' specific adaptation issues.

Uncertainties in climatic impacts, and the social-economic and environmental dynamics in heterogeneous smallholder agriculture can limit evidence-based long-term adaptation planning (Burnham and Ma 2018; Vermeulen et al. 2013). We found that adoption of climate change adaptation measures is itself an adaptive learning process that occurs over time, e.g. risk-averse farmers showed reluctance for the upfront adoption of adaptation measures and instead tended to experiment with small scale trials before broader adoption. While climatic and socioeconomic uncertainties are evident, adaptation policy for smallholder agriculture must be guided by constructing alternative adaptive policy pathways to address transient adaptation needs and barriers (Moallemi et al. 2020b). Flexibility to adapt the policy, if required, in the future as uncertainty unfolds, must be maintained and involving the fullest engagement of relevant stakeholders in the planning process (Kuchimanchi et al. 2021; Moallemi et al. 2020a).

4.4 Limitations

Our study relied on smallholder farmers' responses selected through a stratified random process to ensure representative coverage across agroecosystems. Since adoption and barriers are explicitly rooted in complex socio-ecological systems, caution must be taken when generalising the findings to other regions. We observed variability in the composite indices of adoption and barriers for the Hill and Mountain agroecosystems, which necessitates further fine-scale social research within agroecosystems. We employed stepwise regression to identify the key determinants of barriers for each agroecosystem. Despite the strong potential of the approach to generate recommendations for adaptation policy decisions, further research could better account for theory-driven variables more comprehensively in order to capture the relative influence of those variables on barriers across agroecosystems. Inductive interpretive research at a finer resolution could generate further narratives on the variabilities in adoption of climate change adaptation measures and barriers to adoption for smallholder agriculture in heterogeneous socio-ecological systems.

5 Conclusion

Our empirical approach provided new insights into the adoption of climate change adaptation measures and barriers in smallholder agriculture. We observed spatially varying levels of adoption and barriers across and within agroecosystems. The highest level of adoption of adaptation measures was observed in the Hill agroecosystem while the highest level of adoption barrier was observed for the Terai. Farmers reported employing some adaptation measures more commonly (e.g. crop adjustment, farm management, and fertiliser management) than others. Techno-informational, economic, and environmental barriers were the key impediments to adoption. We found that most determinants of barriers varied spatially except the gender of the household head and the farmer's access to credit that transcended across all agroecosystems. Adaptation programs for smallholder agriculture, including Nepal's National Adaptation Plan, must encourage smallholder farmers to adopt adaptation measures by alleviating the barriers via addressing key determinants which varied across agroecosystems. Results indicate that removing gender-based restrictions to services and opportunities and greater access to credit for adaptation would create opportunities for lowering the adaptation barriers for all agroecosystems. Results further emphasise the need for holistic adaptation policies to account and address all barriers and foster smallholder resilience to climatic change. Construction of alternative adaptive policy pathways, through bottom-up, participatory, and multi-stakeholder engagement could address adaptation barriers while accommodating socio-ecological and climatic uncertainties in smallholder systems towards achieving both near-term and longer-term national production goals.

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Data availability The datasets generated during and/or analysed during the current study are available in Lamichhane et al. (2021).

Declarations

Ethical approval Ethical approval was obtained from the Faculty of Science, Engineering, and Built Environment Human Ethics Advisory Group, Deakin University, Australia (ref. no. STEC-43–2018-LAMICHHANE). Consent to participate in the research was acquired, verbally or in writing based on participant's choice, from all participants. Respondent identities are completely anonymised in the manuscript and the supporting information.

Competing interests The authors declare no competing interests.

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