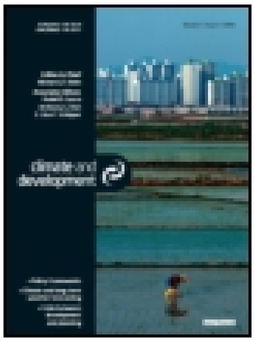

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Multi-level determinants of crop choice to water stress in smallholder irrigation system of Central Nepal

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ABSTRACT

Change in crop choice is a common adaptation strategy for global change. However, its drivers are not well understood. We investigate the multilevel determinants of smallholders' crop choice in irrigated agriculture of Central Nepal. We build upon previous studies and consider four levels of determinants: households, irrigation systems, local and regional market systems, and climatic conditions. Using primary survey data of 316 farmers from 9 farmer-managed irrigation systems in the Trishuli-Narayani sub-basin of Central Nepal, among other results, we document that smallholder farmers are likely to choose rice during the monsoon season if they are experienced and farm in the irrigation systems fed by large rivers. Water stress affects the crop choice mainly in two ways. In irrigation systems fed by large rivers, farmers located towards the tail-end of the canal are less likely to plant rice due to water stress. Farmers living in the irrigation systems that are fed by small and medium-size rivers are more likely to choose less water-demanding crops. Market integration is also a key determinant of crop choice. We discuss the implications of our findings for climate-resilient adaptation strategies in Central Nepal.

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Farmer-managed irrigation systems; rice; adaptation; mountain; crop choice; multilevel model

1. Introduction

Sustainability of rural agriculture and livelihood is increasingly impacted by multi-level drivers of change, including competing water demand, labour migration, market integration, and extreme climate events (Warner et al., 2015). Smallholder farming[1], which accounts for 50 percent of the global farmland and more than half of the world's food production (Samberg et al., 2016), is vulnerable to these stresses because of greater exposure to environmental stresses and limited adaptive capacity (Rapsomanikis, 2017; Roka, 2017). In Nepal, there are 2.7 million farms with an average landholding of 0.5 hectares, which contribute to up to 70 percent of the country's total food production (Rapsomanikis, 2017; Roka, 2017). However, in recent decades, these smallholder farmers have come under increasing stress from urbanization, market integration, water scarcity, competing water demands, and climate variability and change (Bastakoti et al., 2010; Döll, 2002; Pokharel, 2015; Scott et al., 2019).

Water stress[2] in irrigation systems is burgeoning in rural and urban areas of Nepal, partly driven by increasing population, land use changes, and climate variability and change (Scott et al., 2019). It occurs when there is a significant decrease in water supply relative to irrigation demand in the system, driven by a decrease in water availability at the irrigation intake, competing water demand from other sectors, inadequate irrigation infrastructure, and poor water management (Bastakoti et al., 2015; Thapa & Scott, 2019). In particular, along with other changes, Nepal has also witnessed changes in the precipitation trend (Douglas, 2009; Panthi et al., 2015). In the Gandaki River Basin of Central and Western Nepal, where our study sub-basin is located, there is a decreasing trend of pre-monsoon and winter rainfall in the Mountain region. Similarly, from 1966 to 2015, there was an increase in extreme precipitation events in the western mountainous regions and mixed changes in other regions including the Gandaki Basin (Talchabhadel et al., 2018). These changes, along with other drivers of change, contribute to water stress in the irrigation system by altering the intensity and timing of water availability.

To cope with these challenges, farmers have been adapting their agricultural practices (Chhetri et al., 2013), of which change in crop choice is one of the most frequently adopted strategies (Dury et al., 2013). Crop choice is a dynamic process, affected by social, economic, cultural, and biophysical factors (Beckford, 2002; Dury et al., 2013). Among all the crops grown in Nepal, rice is one of the main staple crops and a key constituent of the country's food security. However, rice production is affected by multilevel factors, such as variability of rainfall and market integration. The lowland rice variety, common in Nepal and other Asia countries, consumes 2–3 times more water per hectare than other staple crops (GRiSP, 2003). These water-intensive crops will face significant water stress as climate change worsens the water availability during the pre-monsoon season when there is a high irrigation demand. This, along with the market integration at

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the national and local levels, has been discussed as some of the motivations for farmers to choose cash crops such as vegetables over rice (Thapa et al., 2018). However, to the best of our knowledge, a systematic analysis of the multilevel determinants of crop choice of smallholder farmers in Nepal is lacking.

The main objective of this paper is to assess the multilevel determinants of farmers' crop choice in irrigated agriculture of Central Nepal. Using a survey data of 316 farmers, sampled from 9 farmer-managed irrigation systems (FMIS) in the Trishuli-Narayani sub-basin, we examine the relative importance of household, irrigation system, regional market, and climate conditions as the potential determinants of crop choice. We apply a multilevel discrete choice model to assess the determinants because crop choice decision at a household level is not only affected by the household characteristics but also by multilevel phenomena such as regional market integration and global climate variability and change (Bastakoti et al., 2010; Cifdaloz et al., 2010).

This study contributes to the existing literature in at least three significant areas. First, although rice is the primary staple food crop in Nepal, in recent years, increasing numbers of farmers have opted for other crops such as vegetables and citrus fruits (Piya et al., 2013). The reasons for this change in crop choice have not been comprehensively examined. In particular, to the best of our knowledge, the previous studies have not simultaneously considered the household characteristics, local and regional market conditions, irrigation institutions, and climate-related factors as multilevel determinants of crop choice. Second, studies on the roles of irrigation institutions and collective action on system-level water delivery are limited because they do not account for the contributions of hydrological infrastructure that are affected by regional and global changes. Ghimire et al. (2015) and Upadhyaya et al. (1993) studied factors affecting the adoption of improved rice varieties by including household, farm, institutional, and technology characteristics in Nepal. However, they did not incorporate irrigation system-level factors. Third, irrigation system-level studies are limited in capturing the variability in farmer's decision-making processes at multiple spatial scales including regional and global drivers of change (Bastakoti et al., 2010; Bhatta et al., 2006; Cifdaloz et al., 2010). This study attempts to fill these gaps in the literature by providing a more comprehensive analysis of the multilevel determinants of smallholder farmers' choice of lowland rice during the monsoon season in Central Nepal. We pay attention to the role of water stress, which has strong linkages with climate variability and changes observed in Nepal. Thus, we capture the context of crop choice at multiple levels including climate variability.

The remainder of the paper is organized as follows. In Section 2, we discuss the theoretical framework, which informs the subsequent empirical analysis. Section 3 describes the study area, data, and empirical model. We present the results in Section 4 followed by the discussion and conclusion in Section 5 that also highlights the policy implications of our findings.

2. Theoretical framework

We outline a generalized schematic framework (Figure 1) of crop choice. In this framework, the primary outcome – crop choice decision – is influenced by multilevel factors such as household and socioeconomic factors (e.g. age, education, and income); biophysical and agronomic factors (e.g. climate, slope, and soil type); irrigation system-level factors (e.g. institutional rules and irrigation infrastructure); and market factors (e.g. distance to market and crop marketed) (Table 1). Accordingly, we analyze the multilevel determinants of crop choice in Nepal.

Household and socioeconomic factors: Demographic and socioeconomic characteristics of farmers are the first level of factors that influence their agricultural decisions including crop choice. Age, educational attainment, training, income, and farm size have been identified as important determinants of crop choice and crop diversification (Adesina & Zinnah, 1993; Bezabih & Sarr, 2012; Seo & Mendelsohn, 2008). Younger farmers are more knowledgeable than older farmers about new practices and are willing to bear the risk (Adesina & Zinnah, 1993). The ability to take risks is higher for farmers with larger landholding (Khanal & Mishra, 2017; Langyintuo & Mungoma, 2008). Education, training, and visits by extension services strengthen the farmers' knowledge of new crops and positively affect the crop diversification (Deressa et al., 2009; Tambo & Abdoulaye, 2012).

Biophysical and agronomical factors: The biophysical and agronomical factors such as cropland location, soil type, climate, and slope are significant determinants of crop choice. In Nepal, rice is grown in all agroecological zones, from the subtropical climatic region of the lowland Terai and the valley to the higher altitudes of 1,500 and 3,050 m above sea level – the highest elevations in the world known to grow rice (Chhetri & Easterling, 2010; FAO, 2018b). Our study area is in the Hills and Terai regions which are suitable for rice cultivation. The location of agricultural land in the irrigation system is another biophysical attribute that determines water stress. Generally, tail-end farmers receive less water compared to farmers at the head and middle sections (Lam, 1998). In a hilly area, a slope greater than 45 percent is not considered suitable for holding the water required for rice cultivation (Chhetri & Easterling, 2010). For moderate and less slopy areas (less than 45 percent), the farmers tend to create terrace (also called *khet*) where the land is bunded[3] to make it suitable for puddle rice farming (Rana et al., 2009).

Irrigation system-level factors: Crop choice is also affected by irrigation system-level factors such as hydrological infrastructure and institutional rules of the irrigation system. In Nepal, rice is mostly grown on irrigated plots where irrigation is supplied by FMIS. These irrigation systems are generally built using low-cost technology appropriate for heterogeneous local conditions. Their performance can be measured and assessed by the attributes of farm productivity and delivery of water quality and quantity (Molden et al., 1998; Svendsen & Small, 1990). Studies have shown that FMIS with indigenous water management rules provides more reliable sources of adequate water supply than those managed by government agencies, also called Agency-managed Irrigation Systems (AIMS) (Bastakoti & Shivakoti, 2012; Lam, 1998). For example, the rules devised by the farmers for water distribution and allocation are more flexible to local conditions such as soil type and socioeconomic factors than the rules

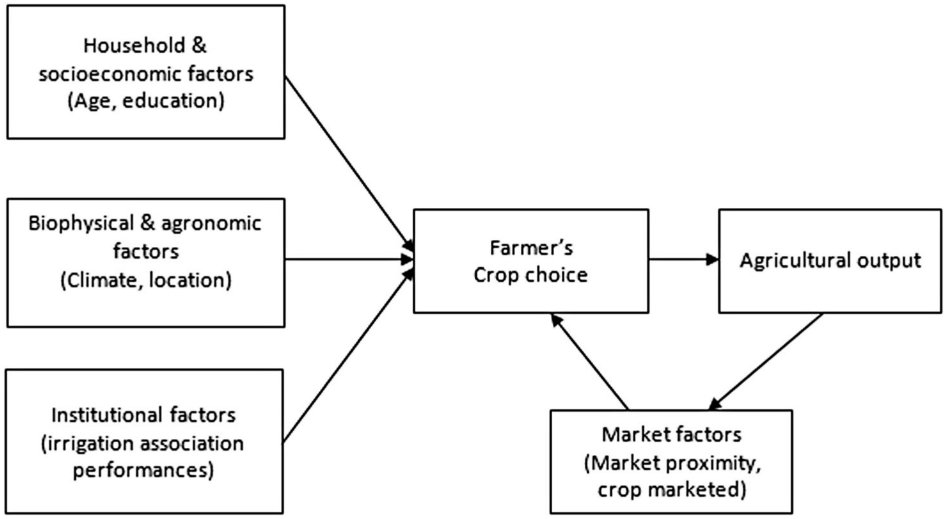

Figure 1. Schematic diagram of key factors affecting farmers' crop choice (Source: Author).

crafted by agency engineers in AIMS who are often located at remote locations and have limited information on the local context.

Market factors: Proximity to market helps farmers in at least two ways. It provides them with easier access to inputs (e.g. hybrid seed, fertilizers, and pesticides). Market proximity also influences farmers' crop choice. For example, vegetables are preferred crops among the farmers located closer to market and road networks (Ghimire et al., 2015; Thapa et al., 2018).

3. Methods

3.1. Study area and data collection

The study area is located in the Trishuli-Narayani sub-basin of the Gandaki River Basin (GRB) of Central and Western Nepal, which has a total catchment area of 46,300 km^2 (Figure 2). Originating in the mountainous region of Central Nepal and Tibet, the Trishuli is a major river system providing water for agriculture, households, and energy for millions of people living in the basin and beyond. Agroecologically, GRB is divided into Mountains, Hills, and Terai region. We chose Trishuli-Narayani sub-basin because it is one of the highly productive basins in the county that also has undergone rapid socio-environmental changes as a result of market integration, urbanization, and environmental degradation.

There are about 350 FMIS in the Trishuli-Narayani sub-basin (DOI, 2007). From a preliminary survey of 25 FMIS, we randomly selected 9 FMIS based on two considerations: the size of the river used for canal intake and the agroecological zone (Table 2). The size of the river used for canal intake directly contributes to water stress and the potential adaptation mechanism. Eight of the FMIS are in the hilly region and one FMIS is in the Terai region. The heterogeneity of agro-ecoregions captures the diversity in climatic conditions, culture, ethnic compositions, which, in turn, influences adaptation (Gentle & Maraseni, 2012).

A comprehensive household survey of farmers was conducted using structured questionnaires during the post-monsoon season of 2016. Approximately 30–45 households were randomly selected from each FMIS, stratified by the canal's head, middle, and tail sections. The sampling was stratified by the sections of the canal because farmers at the tail section are generally more water-stressed than farmers at the head and middle sections of the irrigation system (Anderies & Janssen, 2011; Lam, 1998; Martin & Yoder, 1988).

In addition, 9 focus group discussions (FGD), one in each FMIS, were conducted with the current and previous governing members of the irrigation system also referred to as the Water User Association (WUA). Open-ended questionnaires were used to collect information on the history of irrigation system management, water stress period, coping and adaptation strategies, and infrastructure conditions.

We also conducted a transect walk in each irrigation system (Oudwater & Martin, 2003), where we surveyed the canal from the tail to the head section and estimated the river discharge using field measurements and farmers' insight. This information was used to categorize the river size.

3.2. Measurements of variables

We are interested in analyzing the multilevel determinants of crop choice. Therefore, our dependent variable of interest is crop choice. The crop choice of a farmer is represented by a binary variable that takes the value of 1 if the farmer's choice during the monsoon season (May – September) of 2016 was rice, and 0 if the choice was other crops.[4] Figure 3 shows the frequency distribution of non-rice crops in the sample. The most frequently chosen non-rice crops are vegetable, mainly Cabbage, Cauliflower, Tomato, Radish, Green Peas, Bitter gourd, and Chili pepper.

We capture the context for crop choice at four levels: household, irrigation system, regional, and global. The household-level variables include socio-demographic characteristics like age, education, landholding, income source, and crop intensity (Table 1) We capture the four distinct but related aspects of the irrigation system-level characteristics: hydrological infrastructure, institutional rules, WUA performances, and perceived

Table 1. Description of the key variables.

Type	Variables	Description	Hypothesized effect	Associated literature	Coded
Dependent variable: Crop choice	Rice	Farmer plant rice	NA	NA	Binary (1 = Rice, 0 = Others)
	Other crops	Farmer plant other crops (e.g. vegetables, millet)	NA	NA	Categorical (1 = Fallow, 2 = Other crop, 3 = Rice)[1]
	Fallow	Monsoon crop intensity is less than or equal to 50	NA	NA	
Household and socioeconomic factors	Age of household head	Age of the head of household	+	Adesina and Zinnah (1993); Seo and Mendelsohn (2008)	Discrete
	Education	The education level of the head of the household	+	Below et al. (2012); Bezabih and Sarr (2012); Deressa et al. (2009); Seo and Mendelsohn (2008); Yang et al. (2017)	Categorical (1 = No formal education, 2 = less than 10th grade of education, 3 = 10th grade or higher education)
	Training	Participation in agricultural training in the last 10 years	+	Deressa et al. (2009); Tambo and Abdoulaye (2012)	Dummy (1 = Yes, 0 = No)
	Income from agriculture	Self-reported percentage of income from agriculture	+	Deressa et al. (2009)	Continuous
	Agriculture landholding	Total irrigable landholding in *ropani*	+	Adesina and Zinnah (1993); Becerril and Abdulai (2010); Tambo and Abdoulaye (2012)	Continuous
Biophysical & agronomical factors	Tail-end location	Location of the cropland towards the end of the irrigation canal	-	Abdulai et al. (2011); Lam (1998)	Dummy (1 = Tail, 0 = Other)
	Crop intensity	The fraction of the cultivated area that is harvested that is calculated as the ratio of the harvested irrigated areas over the area equipped for full irrigation	+	NA	Continuous
	Temperature trend	Change in the mean temperature during monsoon season		Bezabih and Sarr (2012); Jain et al. (2015); Moniruzzaman (2015)	Continuous
	Rainfall trend	Change in the mean rainfall during the monsoon season		Bezabih and Sarr (2012); Jain et al. (2015); Moniruzzaman (2015)	Continuous
Market factors	Travel time	Travel time required to travel to the nearby marketplace weighted by mode of transportation. The travel by foot is weighted 2.25 times more than that by automobile.	-	Tambo and Abdoulaye (2012); Waldman et al. (2017)	Continuous
	Crop marketed	Percentage of total crop harvested in a year that is sold in the market			Continuous
Irrigation-system level factors	River category[WUA]	River category based on estimated lean discharge: small-size river (lean flow <1,000 L per seconds), medium-size river (lean flow 1,000 - 10,000 L per seconds), and large-size rivers (lean flow>10,000 L per seconds)	-	NA	Categorical (1 = small, 2 = medium, 3 = large rivers)
	Institutional Rules Index[WUA]	It is the summation of three types of rules and policies of WUA as dummy variables: (i) irrigation water fees, (ii) time-based water allocation rule, (iii) water guards assigned for effective delivery.	NA	Lam (1998)	Discrete (Range: 0–3)
	Performance Index	It is the summation of farmers' perception of four organizational processes and institutional leadership: (i) labour mobilization ability, (ii) financial transparency, (iii) ability to collect external fund, (iv) perception of the social image of the WUA committee members. All variables are dummy variables.	-	Thapa et al. (2016)	Discrete (Range: 0–4)
	Water Delivery Index	It is the summation of farmers' perception of water delivery through five variables: (i) adequacy, (ii) timeliness, (iii) reliability, (iv) deprivation, and (v) flexibility of farmers' access to water. All variables are dummy variables.	-	Lam (1998)	Discrete (Range: 0–5)
Agroecology	Terai	Dummy for Terai region	NA	NA	Dummy (0 = Other, 1 = Terai)

Note: WUA: Irrigation-system level variable, 1: The categorical variable was also used to estimate a multilevel multinomial model of farmers' crop choice. However, we excluded this iteration from our analysis due to the small number of observations on fallow land (n = 21).

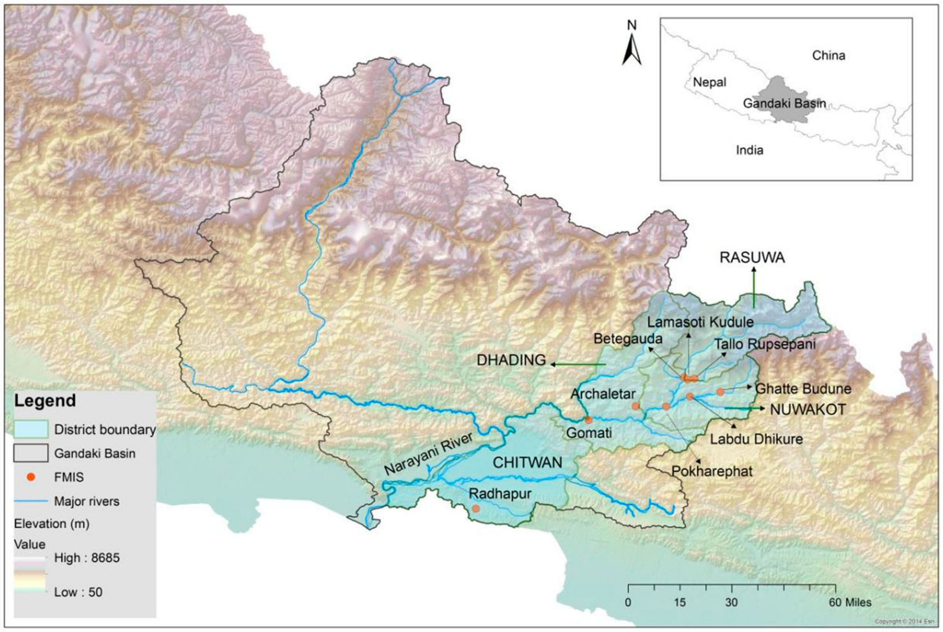

Figure 2. Study area.

water delivery. Distance to market and total crops marketed are used as proxies for regional market integration. Precipitation and temperature trend are used to capture regional and global variables.

The water stress level of an irrigation system is directly linked to its hydrological infrastructure which is captured using two variables: category of water source (river in our case), and percent of the canal that is concrete. FMIS that divert water from large rivers generally have a larger volume of water for distribution compared to the irrigation systems that divert water from small- and medium-sized rivers. The irrigation systems that rely on small water sources are more likely to be water-stressed than those that rely on large sources, which is likely to further worsen with climate variability and change and competing demands for limited water. Therefore, the river is classified into three categories based on river discharge during the lean period: small-size rivers (lean flow <1,000 L per second), medium-size river (lean flow 1,000–10,000 L per second), and large-size rivers (lean flow>10,000 L per seconds).[5] An irrigation system with adequate water can face water stress if the physical infrastructure is not well maintained. Therefore, we include the percent of the canal that is concrete as another indicator of hydrological infrastructure.

Adequate infrastructure is not enough for timely and equitable delivery of water to farmers. Well-crafted rules and enforcement mechanisms are also required (Uphoff, 2005). For example, rules and norms set out by WUA and enforced through voluntary mechanisms can promote behaviors for collective benefits and help maintain the overall agricultural productivity despite poor infrastructure. Following Bastakoti et al. (2015) and Lam (1998), we develop an irrigation system-level index to evaluate the density of institutional rules for water management in an irrigation system. We incorporate three types of rules to construct *Institutional Rules Index* (IRI): irrigation water fee to farmers (F_i), time-based water allocation (R_i)[6], and water guards to deliver water in an effective and timely manner (G_i). The IRI is defined as follows:

$$IRI_i = \sum (F_i + R_i + G_i)$$

Each rule is a dummy variable, which takes the value of 1 if it is present; otherwise 0. Then by construction, IRI_i takes the discrete values between 0 and 3.

One of the common challenges to local institutions is their elite capture and power play that discourages marginal farmers to express their concerns (Iversen et al., 2006; Lund & Saito-Jensen, 2013). The organizational processes such as financial transparency, decision-making processes, and social image of leadership are some of the basic institutional factors that can foster effective adaptation (Gupta et al., 2010; Thapa et al., 2016). We calculate the institutional process, *Performance Index (PI),* based on the farmer's perception of the leadership and institutional processes, which is measured via four dimensions: labour mobilization ability (L_i), financial transparency (T_i), ability to collect external fund (F_i), and the perception

Table 2. Distribution of farmer-managed irrigation systems and households.

	Hills		Terai		Total	
River Category	FMIS	Households	FMIS	Households	FMIS	Households
Small	2	51	0	0	2	51
Medium	2	63	1	38	3	101
Large	4	164	0	0	4	164
Total					9	316

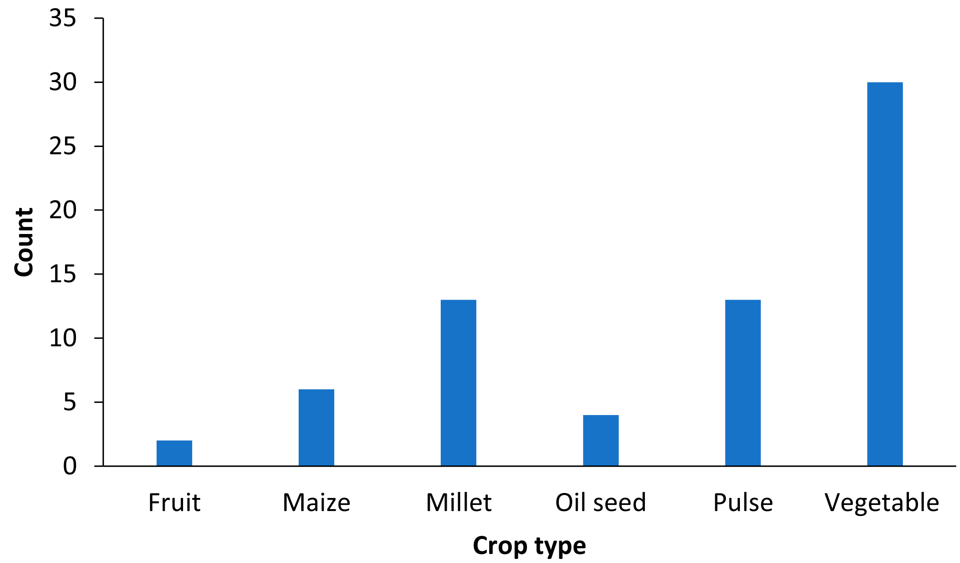

Figure 3. Frequency distribution of non-rice crops.

of the social image of the WUA committee members (S_i). The PI is defined as follows:

$$PI_i = \sum (L_i + T_i + F_i + S_i)$$

All of the variables are dummy variables. Thus, the *PI* score ranges between 0 and 4.

The main function of the irrigation system is to deliver water in an adequate, timely, and fair manner (Martin & Yoder, 1988; Pradhan, 1989). Following Lam (1998), we construct a *Water Delivery Index (WDI)* to capture farmers' perception of water delivery. It is based on five considerations: adequacy (A_i), timeliness (T_i), reliability (R_i), deprivation (D_i), and flexibility (F_i). Water adequacy and timeliness refer to farmers' perception of adequate and timely delivery of water. Farmers achieve reliable water supply when they can predict the availability of water. Equity measures any deprivation on receiving the water whereas flexibility focuses on alteration of the water allocation rules according to the farmers' needs. WDI is defined as:

$$WDI_i = \sum (A_i + T_i + R_i + D_i + F_i)$$

All of the five variables are dummy variables. WDI is a farmer-level variable where WDI_i takes the discrete values between 0 and 5 for farmer *i*.

We include farmers' crop intensity to capture the effects of agricultural productivity on their crop choice (Table 3). Crop intensity, defined as the fraction of cultivated area that is harvested over a year and measured in percentage (FAO, 2018a), is an indicator of agricultural productivity. For example, a 100 percent crop intensity of a farmer means that all the irrigable land is cropped for one season, or partially cropped over multiple seasons (Lam, 1998). Similarly, a crop intensity of 300 signifies that all agricultural land is harvested three times a year.

The level of integration with the local and regional market is an important consideration in farmers' crop choice. The share of the total annual crop harvest that is sold in the market is taken as a proxy for a farmers' level of market integration. We expect that farmers who are more integrated with the

Table 3. Summary statistics.

	Rice ($n = 253$)				Other crop ($n = 63$)			
Variable	Mean	SD	Min	Max	Mean	SD	Min	Max
Age of household head	51.82	13.80	19	79	49.79	11.65	18	76
Education	1.91	0.72	1	3	1.86	0.72	1	3
Training	0.26	0.44	0	1	0.37	0.49	0	1
Agricultural land holding	8.62	6.91	1	39	8.39	6.04	1	26
Income from agriculture	82.27	23.37	25	100	73.41	27.89	20	100
Tail-end location	0.26	0.44	0	1	0.41	0.50	0	1
Crop intensity	274.39	44.79	83	420	219.90	77.08	40	400
Crop marketed	22.50	28.04	0	100	33.15	36.72	0	100
Travel time	1.64	1.14	0.5	5	1.94	1.45	0.5	5
River category	2.49	0.70	1	3	1.81	0.67	1	3
Concrete canal	45.55	20.37	20	75	37.30	17.66	20	75
Institutional Rules Index	1.30	1.15	0	3	1.71	1.14	0	3
Performance Index	7.48	1.00	0	4	3.24	1.17	0	4
Water Delivery Index	8.30	1.35	0	5	2.54	1.49	0	5
Decadal monsoon precipitation trend (Tau)	0.48	0.07	0.37931	0.58621	0.48	0.07	0.37931	0.58621
Decadal monsoon temperature trend (Tau)	0.86	0.01	0.85376	0.88698	0.87	0.01	0.85376	0.88698

Table 4. The Mann-Kendall's tau value for the decadal seasonal trend in precipitation (millimeter/year) in four climate grid-regions of the Gandaki River Basin (1986-2016).

GridID	Pre-monsoon	Monsoon	Post-monsoon	Total monsoon
29	−0.2731**	0.5862***	0.2184	0.0897
40	−0.1914	0.5356***	0.2551**	0.0115
102	−0.1484	0.4942***	0.2230	0.0437
109	−0.0839	0.3793***	0.2919**	−0.0483

*** Trend at α = 0.001 level of significance, **Trend at α = 0.05 level of significance, * Trend at α = 0.10 level of significance.

market produce more cash crops for higher revenue from the nearby market than those that are less integrated. The positive relationship between market proximity and cash crop has been documented in Nepal (Thapa et al., 2018).

Last but not the least, we incorporate the long-term precipitation and temperature trend as the regional and global variables affecting the cropping decision. The data for precipitation and temperature were obtained from the Center for Environmental Data Analysis (CEDA).[7] The monthly total precipitation and average temperature data were obtained from the HadISD dataset (v2.0.2.2017f) for Nepal from 1981 to 2017. The dataset is at 0.5 ° x 0.5° grid scale. In line with Panthi et al. (2015), we group the data into four seasons: pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February). Then we use Mann-Kendall test for monotonic trend, a non-parametric method, to calculate the decadal trend (decadal moving average) since it is more suitable for non-normality in a short record and the presence of outliers (Panthi et al., 2015). The tau and Sen's slope values were calculated using Microsoft Excel's XLSTAT function and Stata version 15 (Tables 4 and 5).

3.3. Multilevel discrete choice model

A farmer's crop choice is modeled as an outcome of a multilevel discrete choice process, where crop choice is a binary decision between monsoon rice and other crops. Multilevel models are commonly used for analyzing hierarchical and nested relationships (Goldstein, 1997; McCord et al., 2018). By the nature of our sample design, the farmers are nested at four levels of hierarchies: a farmer is nested within FMIS and the FMIS is nested in an economic region (e.g. local and regional market), which is nested within one of the four climate regions. Consequently, farmers from the same FMIS and climate region are expected to face similar institutional and climatic environment. Multilevel models are also robust for smaller group sizes (Moineddin et al., 2007), which in our case is 9 FMIS and 4 climate regions.

Following (Goldstein, 1997), we estimate versions of the following basic regression model:

$$y_{ij} = \beta_0 + \beta_1 x_{ij} + (u_{0j} + u_{1j}x_{ij} + e_{0ij})$$

$$var(e_{0ij}) = \sigma^2_{e0}$$

where j is for the institutional class ($j = 1 \ldots$ J) and i is a farmer ($i = 1 \ldots n_j$). y_{ij} is crop choice, x_{ij} a vector of explanatory variables, u_{0j} & u_{1j} are the fixed residual variables at two levels, and e_{0ij} is the overall residual term.

4. Results

The result from the multilevel discrete choice model is presented in Table 6. It highlights the determinants of crop choice at household, irrigation system, regional and global levels. At the household level, age is a significant determinant of crop choice. Elder farmers are more likely to choose rice over other crops. The educational attainment and training of farmers are not significant, suggesting that they are not constraints to the adoption of non-rice crops that are technologically less advanced. Landholding size is also not a significant factor. But this is not a surprising result, given that our sample consists mostly of smallholder farmers in the Hills that have smaller landholding size than farmers in the Tarai region.

The household crop intensity has a small but positive effect on the choice of rice, which can be partly explained by two reasons. First, the farmers who choose other crops over rice may fallow a section of their land for some time to accommodate the crop cycle of non-rice crops. For example, in Gomati FMIS, located in the hilly district of Dhading, farmers left their

Table 5. The Mann-Kendall's tau value for the decadal seasonal trend in temperature (o C) in four climate grid-regions of the Gandaki River Basin (1986-2016).

GridID	Pre-monsoon	Monsoon	Post-monsoon
29	0.7204***	0.8698***	0.5194***
40	0.7621***	0.8870***	0.5582***
102	0.7535***	0.8538***	0.5409***
109	0.7720***	0.8624***	0.5856***

*** Trend at α = 0.001 level of significance, **Trend at α = 0.05 level of significance, * Trend at α = 0.10 level of significance.

Table 6. Multilevel determinants of crop choice.

Crop choice (1 = Rice,0 = Other crops)	Odd Ratio	SE
Age of household head	1.03269**	0.018677
Education	0.75736	0.255918
Training	0.611345	0.27992
Agricultural landholding	1.057685	0.03864
Income from agriculture	1.010129	0.008811
Tail-end location	0.017303**	0.035784
Crop marketed	0.973104**	0.011516
Travel time	0.84415	0.169135
River category	16.02565***	1.17E+01
Concrete canal	1.02342	0.033574
Institutional Rules Index	0.402227	0.265245
Performance Index	1.242765	0.343859
Water Delivery Index	1.104347	0.208382
Decadal monsoon precipitation trend (Tau)	7.20E+10**	7.08E+11
Decadal monsoon temperature trend (Tau)	9.48E-27**	2.30E-25
Crop intensity	1.014295***	0.004887
Tail-location x crop marketed	1.02297	0.016562
Tail-location x crop intensity	1.010071	0.00794
Terai dummy	0.056221	1.19E-01
Constant	7.75E+13	5.87E+14
Random effect		
Variance -climate region	4.03E-34	8.14E-18
Variance – FMIS institutions	8.11E-36	2.92E-18
Wald Chi^2	58.31	
Log-likelihood	−81.3194	
Number of observations	316	
Number of FMIS institutions	9	
Number of climate regions	4	

*** Significant at 1%, ** Significant at 5%, * Significant at 10%.

land fallow for a month after harvesting maize in June/July because they intended to sow radish in September/October. Second, some farmers leave part of their agricultural plot fallow for a few months because of water scarcity and other factors.

At the irrigation system level, we find that water stress affects crop choice via two distinct mechanisms. Within an irrigation system, we find that farmers at the tail-section of the irrigation system are less likely to farm rice than those at the head and the middle sections of the systems. A farmer at Tallo Rupsepani FMIS in Rasuwa district said, "Since I am at the tail-end, I have to wait for a quite long time until the farmers at the head and middle sections of the canal irrigate their plots, as a result, I sometimes hardly get the water on time to prepare my land for rice cultivation." Thus, the farmers at the tail-sections of the systems can be expected to choose non-rice crops, requiring less water, due to water shortage exacerbated by climate variability and change.

The size of the irrigation source, which is a river in our case, is another irrigation system-level variable that influences water stress and therefore the crop choice. The irrigation system that diverts water from large rivers is more likely to choose rice over other crops, compared to farmers in an irrigation system that diverts water from small- and medium-sized rivers. The farmers located in large rivers have plenty of water to divert during the pre-monsoon season for rice cultivation, whereas the farmers fed by small- and medium-sized rivers have limited supply to distribute. They often face seasonal water stress during the pre-monsoon and dry period which limits their crop choice.

At the irrigation system level, we also consider institutional characteristics via three indices. However, the IRI, PI, and WDI are not significant. This could be due to the lack of variability in the variables that constitute the indices (Table 3). However, the WDI becomes a significant determinant of crop choice when irrigation system-level variables (e.g. IRI, river category, and concrete canal) are dropped from the model (Table 7). This suggests with better water delivery, farmers are more likely to choose rice crop during monsoon season.

The crop choice is also influenced by regional and global factors, notably the market integration and climate variability and change. One of the variables of market integration, the crop sold in the market, is negatively associated with paddy farmers. For a one percent increase in the share of total crop harvest sold in the market, the odds of choosing rice crop decrease by a factor of 0.97. This implies that the rice farmers may be motivated by self-consumption. Conversely, the farmers who plant other crops may be harvesting cash crops, mainly the vegetables, instead of rice to be sold in the market.

We also find that climate variability and change is a significant determinant of crop choice. The monsoon precipitation trend is significantly increasing in all the study areas whereas the pre-monsoon precipitation trend is decreasing only in the Terai region (Tables 4 and 5). Similarly, the post-monsoon trend is slightly increasing in some hilly and mountainous regions. In contrast, there is a consistently increasing temperature trend in the study area. For every unit increase in the monsoon precipitation, the odd ratio for choosing rice increases more than that for temperature. The increase in monsoon precipitation increases water availability, which in turn, increases the odds of choosing rice over other crops.

4.1. Further robustness check

The robustness check is conducted to assess the sensitivity of the results to exclusion of correlated factors. From Table 7, we find that WDI becomes statistically significant when the other irrigation system-level factors are excluded from the model (see Specification 1). This suggests that farmers are more likely to choose rice crop over other crops if they perceive water is being delivered effectively.

Table 7. Further robustness check.

	Specification 1		Specification 2		Specification 3	
Binomial model (1 = Rice,0 = Other crops)	Odd ratio	Std. Err.	Odd ratio	Std. Err.	Odd ratio	Std. Err.
Household-level variables						
Age of household head	1.02200	0.01427	1.03030*	0.01848	1.03269*	0.01868
Education	1.36610	0.35533	0.78701	0.25850	0.75736	0.25592
Training	0.62743	0.23010	0.55358	0.24857	0.61135	0.27992
Agricultural landholding	1.00182	0.02828	1.05394	0.03828	1.05769	0.03864
Income from agriculture	1.01201*	0.00724	1.01227	0.00896	1.01013	0.00881
Tail-end location	0.34904	0.52973	0.039811*	0.07583	0.017302**	0.03578
Crop intensity	1.01420***	0.00428	1.01454***	0.00491	1.01429***	0.00489
Crop marketed	0.98223**	0.00726	0.96985***	0.01109	0.97310**	0.01152
Travel time	0.84416	0.10955	0.80047	0.16074	0.84415	0.16913
Performance Index	0.97096	0.16309	1.04949	0.26071	1.24277	0.34386
Water Delivery Index	1.48119***	0.17999	1.13804	0.21590	1.10435	0.20838
Tail-location x Crop marketed	1.00285	0.01287	1.02424	0.01584	1.02297	0.01656
Tail-location x crop intensity	1.00316	0.00632	1.00663	0.00737	1.01007	0.00794
Terai dummy	3.40441	2.84543	0.83863	1.17765	0.05622	0.11854
Constant	0.00702***	0.01160	0.00048***	0.00116	2.75E+13	5.87E+14
Irrigation system-level variables						
River category			15.26793***	9.86745	16.02565***	11.66761
Concrete canal (percent)			0.97980	0.02241	1.02342	0.03357
Institutional Rules Index			0.63231	0.25344	0.40223	0.26524
Regional variables						
Decadal monsoon precipitation trend (Tau)					7.2 E +10**	7.08E+11
Decadal monsoon temperature trend (Tau)					9.48E-27**	0.00000

However, when irrigation-system level factors are included, three changes occur at household level variables – age of household and interaction effect of crop marketed at tail-end location becomes statistically significant, and the WDI becomes statistically insignificant. These changes suggest that institutional characteristics capture the dynamics that are reflected in household characteristics. When regional climatic trends are included, the income from agriculture and crop marketed at the tail section of the irrigation system are rendered insignificant.

5. Discussion and conclusion

5.1. Discussion

The increasing globalization and global environmental change generate a highly interconnected system in which decisions at small scales are influenced by and influence processes at the global scale in unpredicted and novel ways (Anderies & Janssen, 2011). In this paper, we attempt to understand the multi-level determinants of crop choice in the context of irrigated agriculture. More specifically, we study the influence of the multi-level processes to smallholder farmers who produce a significant amount of the world's food. We focus on factors at four levels: household, irrigation system, regional, and global levels.

Since crop choice decisions are made by individuals, it is affected by their household socio-demographic characteristics. We found that older farmers are more likely to choose rice than other crops. This is consistent with the previous studies that show that younger farmers are more likely to take risks and adopt new or alternative crops than older farmers (Adesina & Zinnah, 1993; Bezabih & Sarr, 2012; Yang et al., 2017). Education and training are insignificant determinants of rice crop choice, but it may hold significant for crops like mushrooms that involves advance technology (Lambert & Ozioma, 2011). Landholding size is also not a significant factor, which on the face of it seems contrary to previous findings (Adesina & Zinnah, 1993; Becerril & Abdulai, 2010). However, since the study area is mostly located in the Hills, most farmers have small landholding size.

The crop choice is also affected by water stress that is driven by two irrigation system-level factors – the hydrological infrastructure of the irrigation system and farmers' location within that system. Since rice cultivation requires a significant amount of water during the pre-monsoon season, farmers prefer rice cultivation only if the irrigation system has a consistent supply of water, which is generally possible in sources fed by large and medium-sized rivers. However, within the irrigation system, farmers at the tail-end of the canal are less likely to farm rice than those at the head and the middle end. This is partly because farmers at the tail-end generally receive less water due to seepage loss and potential theft by farmers located above them which are also documented in other regions (Janssen et al., 2011; Lam, 1998).

In addition to the individual and irrigation system-level factors, it is important to understand the role of the market in farmers' crop choice decisions. We find that those who produce for markets are more likely to choose non-rice crops. Rice is generally replaced with vegetables as they are grown mostly to sell in the market. Switching to cash crops is a common adaptation and coping mechanism for smallholder farmers in Nepal and other regions (Bhattarai et al., 2015; D'haen et al., 2014). Also, the economic return from agriculture production, facilitated by access to the market, is a strong determinant of crop choice (Ghimire et al., 2015).

At the irrigation system level, the variables IRI, PI, and WDI are insignificant determinants of crop choice. While these indices capture distinct but related aspects of irrigation system characteristics, the statistical significance of WDI, in particular, signifies that it is sensitive to the inclusion of other indices and measures of irrigation system characteristics. This suggests that rice, which requires more water, is more likely to be the crop choice in irrigation systems that have good water delivery system in place. These rules help farmers towards adequate and equitable water delivery for water-intensive crops such as rice.

Finally, the larger-scale patterns of climate variability and change also affect household-level crop choice decisions. We find that the decadal monsoon precipitation trend is significant and has a positive effect on rice crop choice. Likewise, the decadal monsoon temperature trend is significant and has a negative effect on rice crop choice. This suggests that the region with higher precipitation trends may lead farmers to choose rice crop, whereas, in the areas with lower precipitation, farmers may opt for less water-intensive crops such as vegetables. However, since the variability in timing and intensity of precipitation is critical for agricultural decision making, climate change will likely affect them (Krishnan et al., 2019; Turner & Annamalai, 2012).

5.2. Policy implications

Crop choice is a commonly used coping and adaptation strategy by many smallholder farmers across developing countries (Moniruzzaman, 2015; Piya et al., 2013). Therefore, a sound understanding of the multilevel factors of crop choice by smallholder farmers has important policy implications for food security and agricultural adaptation to global change.

This study highlights the spatial dimension of crop choice in the context of irrigated agriculture and water stress. Farmers at the tail-end of the canal and those in irrigation system fed by seasonal springs are subject to more water stress compared to those located in the head – and middle-sections of the canal and in the systems fed by large rivers. While irrigation infrastructure can help to cope with water stress (Finger et al., 2011), smallholder farmers can be vulnerable to water stress due to their location within the system and the system's hydrological characteristics. These factors need to be considered in understanding the climate vulnerability of smallholder farmers and effective adaptation actions.

Beside climate variability and change, agricultural decision makings are also influenced by regional markets (Bastakoti et al., 2010). This study identifies market integration and climate variability and change as two regional and global drivers of change affecting the crop choice. The effective adaptation programmes must consider all the drivers and their possible interactions, beyond the individual characteristics of farmers.

The study also highlights the need to focus on institutional strengthening. At the irrigation system level, we find that the WDI that captures water delivery in adequate, timely and fair manner is an important determinant of rice crop choice when hydrological infrastructure is not incorporated. This suggests that adequacy and timeliness of water delivery are critical for rice crop choice. Thus, our findings echo the importance of policies that strengthen community-based institutions as an adaptation strategy (Amaru & Chhetri, 2013; Rodima-Taylor, 2012; Thapa & Scott, 2019).

Our findings also have direct implications for the food security of smallholding farmers in Nepal. Since rice is a staple crop in Nepal, it is a preferred crop choice of smallholder farmers. But its cultivation will become increasingly less feasible especially in water stress areas. We find that older farmers are more likely to choose rice over other crops, controlling for the effects of other multilevel factors. This suggests targeted outreach education may be required in the region to strengthen food security and agricultural adaptation. Another implication of our finding is that farmers in less water stress areas are more likely to continue with rice cultivation, which may hinder achieving higher productivity and returns from switching to non-rice crops (e.g. vegetables).

5.3. Limitation

Our study has at least two limitations that must be taken into consideration while interpreting the results. First, we measure market integration as the share of total annual crop harvest that is sold in the market and travel time to the nearby market as proxies for farmer level market integration. While they are expected to be highly correlated with actual market integration, they are not perfect measures as market integration depends on a variety of demand and supply factors. Second, our measures of irrigation system characteristics have limitations. For example, IRI is measured at the irrigation system level, which means it has less variability. Similarly, while we measure PI and WDI following earlier studies, they could have been even more comprehensive if more detailed data were available.

5.4. Conclusion

We analyze the multilevel determinants of rice crop choice during monsoon season in Central Nepal. Among the household level factors, we find that older farmers are more likely to choose rice over non-rice crops than younger farmers. Water stress affects crop choice in two ways. First, within an irrigation system, farmers located at the tail section of the canal are more likely to plant other crops than the farmers at the head and middle section of the canal due to water shortages. Second, the farmers in the irrigation systems that are fed by large rivers are likely to choose rice over non-rice crops. In contrast, in the irrigation systems that are fed by small- and medium-size rivers, farmers are likely to choose less water-demanding crops. Market integration is one of the key regional determinants of crop choice. Farmers with greater market integration are likely to choose non-rice crops. We also find that regional precipitation and temperature trends directly affect the irrigation system and farmers' crop choice. The increasing trend of monsoon precipitation positively influences farmers to choose rice while the temperature trend has the opposite effect. Understanding the multi-level determinants of crop choice contributes to agricultural adaptation and food security policies.

Notes

1. Farms with less than 0.2–0.5 hectares.
2. It refers to supply of water relative to a farmer's perceptions of the irrigation demand for the crop at a given period of time (Yoder, 1994). It is a result of biophysical and climatic changes, infrastructure conditions, institutional rules of water allocation and distribution, and socioeconomic status of farmers.
3. Bunds are corners of the irrigated land that is raised by a few centimeters to hold water.
4. Alternatively, we define crop choice as a categorical variable (1= rice, 2= non-rice crop, 3=fallow land) and estimate a multinomial model of crop choice. We note that observations on fallow land is very small ($n = 21$).
5. We do not include the length of command area canal since it is highly correlated with the hydrological infrastructure.
6. The default is order-based water rotation system (e.g., head to tail).
7. Center for Environmental Data Analysis. (2016). Retrieved from: http://catalogue.ceda.ac.uk.

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References

Abdulai, A., Owusu, V., & Bakang, J. E. A. (2011). Adoption of safer irrigation technologies and cropping patterns: Evidence from Southern Ghana. *Ecological Economics*, *70*(7), 1415–1423. https://doi.org/10.1016/j.ecolecon.2011.03.004

Adesina, A. A., & Zinnah, M. (1993). Technology characteristics, famers' perceptions, and adoption decisions: A tobit model application in Sierra Leone. *Agricultural Economics*, *9*(4), 297–311. https://doi.org/10.1111/j.1574-0862.1993.tb00276.x

Amaru, S., & Chhetri, N. B. (2013). Climate adaptation: Institutional response to environmental constraints, and the need for increased flexibility, participation, and integration of approaches. *Applied Geography*, *39*, 128–139. https://doi.org/10.1016/j.apgeog.2012.12.006

Anderies, J. M., & Janssen, M. A. (2011). The fragility of robust social-ecological systems. *Global Environmental Change*, *21*(4), 1153–1156. https://doi.org/10.1016/j.gloenvcha.2011.07.004

Bastakoti, R. C., Ale, M., Sharma, P., & Shivakoti, G. (2015). Robustness-vulnerability characteristics of irrigation systems in Nepal. In P. Pradhan, U. Gautam, & N. M. Joshi (Eds.), *Small scale irrigation systems: Challenges to Sustainable livelihood* (pp. 77–92). Farmer Managed Irrigation Systems Promotion Trust.

Bastakoti, R. C., & Shivakoti, G. P. (2012). Rules and collective action: An institutional analysis of the performance of irrigation systems in Nepal. *Journal of Institutional Economics*, *8*(02), 225–246. https://doi.org/10.1017/S1744137411000452

Bastakoti, R. C., Shivakoti, G. P., & Lebel, L. (2010). Local irrigation management institutions mediate changes driven by external policy and market pressures in Nepal and Thailand. *Environmental Management*, *46*(3), 411–423. https://doi.org/10.1007/s00267-010-9544-9

Becerril, J., & Abdulai, A. (2010). The impact of improved maize varieties on poverty in Mexico: A propensity score-matching approach. *World Development*, *38*(7), 1024–1035. https://doi.org/10.1016/j.worlddev.2009.11.017

Beckford, C. L. (2002). Decision-making and innovation among small-scale yam farmers in central Jamaica: A dynamic, pragmatic and adaptive process. *Geographical Journal*, *168*(3), 248–259. https://doi.org/10.1111/1475-4959.00052

Below, T. B., Mutabazi, K. D., 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. https://doi.org/10.1016/j.gloenvcha.2011.11.012

Bezabih, M., & Sarr, M. (2012). Risk preferences and environmental uncertainty: Implications for crop diversification decisions in Ethiopia. *Environmental and Resource Economics*, *53*(4), 483–505. https://doi.org/10.1007/s10640-012-9573-3

Bhatta, K. P., Ishida, A., Taniguchi, K., & Sharma, R. (2006). Performance of agency-managed and farmer-managed irrigation systems: A comparative case study at Chitwan, Nepal, Irrigation and Drainage Systems, *20*(2–3), 177–191. https://doi.org/10.1007/s10795-005-9001-8

Bhattarai, B., Beilin, R., & Ford, R. (2015). Gender, agrobiodiversity, and climate change: A study of adaptation practices in the Nepal Himalayas. *World Development*, *70*, 122–132. https://doi.org/10.1016/j.worlddev.2015.01.003

Chhetri, N. B., & Easterling, W. E. (2010). Adapting to climate change: Retrospective analysis of climate technology interaction in the rice-based farming system of Nepal. *Annals of the Association of American Geographers*, *100*(5), 1156–1176. https://doi.org/10.1080/00045608.2010.518035

Chhetri, N., Subedi, M., & Ghimire, S. (2013). Niche-based responses in addressing the climatic constraints to farm production: Analogues to climate-change adaptation in Nepal. *Climate and Development*, *5*(2), 174–181. https://doi.org/10.1080/17565529.2013.789790

Cifdaloz, O., Regmi, A., Anderies, J., & Rodriguez, A. (2010). Robustness, vulnerability, and adaptive capacity in small-scale social-ecological systems: The Pumpa irrigation system in Nepal. *Ecology and Society*, *15*(3). https://doi.org/10.5751/ES-03462-150339

Deressa, T. T., Hassan, R. M., 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. https://doi.org/10.1016/j.gloenvcha.2009.01.002

D'haen, S. A. L., Nielsen, J. Ø., & Lambin, E. F. (2014). Beyond local climate: Rainfall variability as a determinant of household nonfarm activities in contemporary rural Burkina Faso. *Climate and Development*, *6*(2), 144–165. https://doi.org/10.1080/17565529.2013.867246

DOI. (2007). *Development of database for irrigation development in Nepal.*

Döll, P. (2002). Impact of climate change and variability on irrigation requirements: A global perspective. *Climatic Change*, *54*(3), 269–293. https://doi.org/10.1023/A:1016124032231

Douglas, I. (2009). Climate change, flooding and food security in south Asia. *Regional Environmental Change*, *1*, 127–136. https://doi.org/10.1007/s12571-009-0015-1

Dury, J. Ô., Garcia, F., Reynaud, A., & Bergez, J. E. (2013). Cropping-plan decision-making on irrigated crop farms: A spatio-temporal analysis. *European Journal of Agronomy*, *50*, 1–10. https://doi.org/10.1016/j.eja.2013.04.008

FAO. (2018a). *AQUASTAT Glossary*. Food and Agriculture Organization of the United Nations. http://www.fao.org/nr/water/aquastat/data/glossary/search.html?termId=7207&submitBtn=s&cls=yes

FAO. (2018b). *Global Agro-Ecological Zones*. http://www.fao.org/nr/gaez/en/#

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*(3–4), 509–528. https://doi.org/10.1007/s10584-010-9931-5

Gentle, P., & Maraseni, T. N. (2012). Climate change, poverty and livelihoods: Adaptation practices by rural mountain communities in Nepal. *Environmental Science & Policy*, *21*, 24–34. https://doi.org/10.1016/j.envsci.2012.03.007

Ghimire, R., Huang, W. C., & Shrestha, R. B. (2015). Factors affecting adoption of improved rice varieties among rural farm households in Central Nepal. *Rice Science*, *22*(1), 35–43. https://doi.org/10.1016/j.rsci.2015.05.006

Goldstein, H. (1997). *Multilevel statistical models* (4th ed.). John Wiley & Sons Ltd. https://doi.org/10.2307/1534624

GRiSP. (2003). *Rice Almanac* (4th ed.). International Rice Research Institute. https://doi.org/10.1093/aob/mcg189

Gupta, J., Termeer, C., Klostermann, J., Meijerink, S., van den Brink, M., Jong, P., Nooteboom, S., & Bergsma, E. (2010). The adaptive capacity Wheel: A method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environmental Science and Policy*, *13*(6), 459–471. https://doi.org/10.1016/j.envsci.2010.05.006

Iversen, V., Chhetry, B., Francis, P., Gurung, M., Kafle, G., Pain, A., & Seeley, J. (2006). High value forests, hidden economies and elite capture: Evidence from forest user groups in Nepal's Terai. *Ecological Economics*, *58*(1), 93–107. https://doi.org/10.1016/j.ecolecon.2005.05.021

Jain, M., Naeem, S., Orlove, B., Modi, V., & DeFries, R. S. (2015). Understanding the causes and consequences of differential decision-making in adaptation research: Adapting to a delayed monsoon onset in Gujarat, India. *Global Environmental Change*, *31*, 98–109. https://doi.org/10.1016/j.gloenvcha.2014.12.008

Janssen, M. A., Anderies, J. M., & Cardenas, J.-C. (2011). Head-enders as stationary bandits in asymmetric commons: Comparing irrigation experiments in the laboratory and the field. *Ecological Economics*, *70*(9), 1590–1598. https://doi.org/10.1016/j.ecolecon.2011.01.006

Khanal, A. R., & Mishra, A. K. (2017). Enhancing food security: Food crop portfolio choice in response to climatic risk in India. *Global Food Security*, *12*, 22–30. https://doi.org/10.1016/j.gfs.2016.12.003

Krishnan, R., Shrestha, A. B., Ren, G., Rajbhandari, R., Saeed, S., Sanjay, J., Syed, Md. A., Vellore, R., Xu, Y., You, Q., & Ren, Y. (2019). Unravelling climate change in The Hindu Kush Himalaya: Rapid warming in the mountains and increasing extremes. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya Assessment* (pp. 57–97). Springer International Publishing. https://doi.org/10.1007/978-3-319-92288-1_3

Lam, W. F. (1998). *Governing irrigation systems in Nepal: Institutions, infrastructure, and collective action* (1st ed.). Institute for Contemporary Studies.

Lam, W. F., & Ostrom, E. (2010). Analyzing the dynamic complexity of development interventions: Lessons from an irrigation experiment in Nepal. *Policy Sciences*, *43*(1), 1–25. https://doi.org/10.1007/s11077-009-9082-6

Lambert, O., & Ozioma, A. F. (2011). Adoption of improved agroforestry technologies among contact farmers in Imo State, Nigeria. *Asian Journal of Agriculture and Rural Development*, *2*(1), 1–9.

Langyintuo, A. S., & Mungoma, C. (2008). The effect of household wealth on the adoption of improved maize varieties in Zambia. *Food Policy*, *33* (6), 550–559. https://doi.org/10.1016/j.foodpol.2008.04.002

Lund, J. F., & Saito-Jensen, M. (2013). Revisiting the issue of elite capture of participatory initiatives. *World Development*, *46*, 104–112. https://doi.org/10.1016/j.worlddev.2013.01.028

Martin, E. D., & Yoder, R. (1988). A comparative description of two farmer-managed irrigation systems in Nepal. *Irrigation and Drainage Systems*, *2*(2), 147–172. https://doi.org/10.1007/BF01102924

McCord, P., Waldman, K., Baldwin, E., Dell'Angelo, J., & Evans, T. (2018). Assessing multi-level drivers of adaptation to climate variability and water insecurity in smallholder irrigation systems. *World Development*, *108*, 296–308. https://doi.org/10.1016/j.worlddev.2018.02.009

Moineddin, R., Matheson, F. I., & Glazier, R. H. (2007). A simulation study of sample size for multilevel logistic regression models. *BMC Medical Research Methodology*, *7*(1), 1–10. https://doi.org/10.1186/1471-2288-7-34

Molden, D., Sakthivadivel, R., Perry, C. J., De Fraiture, C., & Kloezen, W. H. (1998). Indicators for comparing performance of irrigated agricultural systems. In *IWMI Research Report 20*. https://doi.org/10.3910/2009.028

Moniruzzaman, S. (2015). Crop choice as climate change adaptation: Evidence from Bangladesh. *Ecological Economics*, *118*, 90–98. https://doi.org/10.1016/j.ecolecon.2015.07.012

Oudwater, N., & Martin, A. (2003). Methods and issues in exploring local knowledge of soils. *Geoderma*, *111*(3–4), 387–401. https://doi.org/10.1016/S0016-7061(02)00273-2

Panthi, J., Dahal, P., Shrestha, M., Aryal, S., Krakauer, N., Pradhanang, S., Lakhankar, T., Jha, A., Sharma, M., & Karki, R. (2015). Spatial and temporal variability of rainfall in the Gandaki River Basin of Nepal himalaya. *Climate*, *3*(1), 210–226. https://doi.org/10.3390/cli3010210

Piya, L., Maharjan, K. L., & Joshi, N. P. (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. https://doi.org/10.1007/s10113-012-0359-5

Pokharel, A. (2015). *Towards a theory of sustained cooperation* (No. 2015–25; Watson Institute for International Studies Research). https://doi.org/10.2139/ssrn.2592999

Pradhan, P. (1989). *Patterns of irrigation organization in Nepal: A comparative study of 21 farmer-managed irrigation systems*. International Water Management Institute.

Rana, R. B., Garforth, C. J., & Sthapit, B. R. (2009). Farmers' management of rice varietal diversity in the mid-hills of Nepal: Implications for on-farm conservation and crop improvemen. *Plant Genetic Resources*, *7* (1), 50–62. https://doi.org/10.1017/S1479262108048259

Rapsomanikis, G. (2017). The economic lives of smallholder farmers: An analysis based on household data from nine countries. In *Food and Agriculture Organization of the United Nations*. https://doi.org/10.1016/j.rausp.2016.10.004

Rodima-Taylor, D. (2012). Social innovation and climate adaptation: Local collective action in diversifying Tanzania. *Applied Geography*, *33*, 128–134. https://doi.org/10.1016/j.apgeog.2011.10.005

Roka, H. (2017). The status of smallholder farmers in Nepal's agricultural development strategy (2015–2035). *Agrarian South: Journal of Political Economy*, *6*(3), 354–372. https://doi.org/10.1177/2277976017745197

Samberg, L. H., Gerber, J. S., Ramankutty, N., Herrero, M., & West, P. C. (2016). Subnational distribution of average farm size and smallholder contributions to global food production Subnational distribution of average farm size and smallholder contributions to global food production. *Environmental Research Letters*, *11*(12), 1–11. https://doi.org/10.1088/1748-9326/11/12/124010

Scott, C. A., Zhang, F., Mukherji, A., Immerzeel, W., Mustafa, D., & Bharati, L. (2019). Water in The Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya Assessment* (pp. 257–299). Springer International Publishing. https://doi.org/10.1007/978-3-319-92288-1_8

Seo, S. N., & Mendelsohn, R. (2008). An analysis of crop choice: Adapting to climate change in South American farms. *Ecological Economics*, *67* (1), 109–116. https://doi.org/10.1016/j.ecolecon.2007.12.007

Svendsen, M., & Small, L. E. (1990). Farmer's perspective on irrigation performance. *Irrigation and Drainage Systems*, *4*(4), 385–402. https://doi.org/10.1007/BF01103716

Talchabhadel, R., Karki, R., Thapa, B. R., Maharjan, M., & Parajuli, B. (2018). Spatio-temporal variability of extreme precipitation in Nepal. *International Journal of Climatology*, *May* 2017, 4296–4313. https://doi.org/10.1002/joc.5669

Tambo, J. A., & Abdoulaye, T. (2012). Climate change and agricultural technology adoption: The case of drought tolerant maize in rural Nigeria. *Mitigation and Adaptation Strategies for Global Change*, *17* (3), 277–292. https://doi.org/10.1007/s11027-011-9325-7

Thapa, B., & Scott, C. (2019). Institutional strategies for climate change adaptation in irrigation systems of Nepal. *International Journal of Commons*, *13*(2), 892–908. http://doi.org/10.5334/ijc.901.

Thapa, B., Scott, C., Wester, P., & Varady, R. (2016). Towards characterizing the adaptive capacity of farmer-managed irrigation systems: Learnings from Nepal. *Current Opinion in Environmental Sustainability*, *21*(March), 37–44. https://doi.org/10.1016/j.cosust.2016.10.005

Thapa, G., Kumar, A., Roy, D., & Joshi, P. K. (2018). Impact of crop diversification on rural poverty in Nepal. In *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie* (Vol. 66). https://doi.org/10.1111/cjag.12160

Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. *Nature Climate Change*, *2*(8), 587–595. https://doi.org/10.1038/nclimate1495

Upadhyaya, Hari K., David, C. C., Thapa, Ganesh B., & Otsuka, K. (1993). Adoption and productivity impact of modern rice varieties in Nepal. *The Developing Economies*, *XXXI*(1), 122–37.

Uphoff, N. (2005). Social capital and irrigation management: Bringing rigor and evidence to the relationship. In G. P. Shivakoti, D. L. Vermillion, W. Lam, E. Ostrom, U. Pradhan, & R. Yoder (Eds.), *Asian irrigation in transition: Responding to challenges* (1st ed, pp. 45–78). Sage Publications.

Waldman, K. B., Blekking, J. P., Attari, S. Z., & Evans, T. P. (2017). Maize seed choice and perceptions of climate variability among smallholder farmers. *Global Environmental Change*, *47*(October), 51–63. https://doi.org/10.1016/j.gloenvcha.2017.09.007

Warner, B. P., Kuzdas, C., Yglesias, M. G., & Childers, D. L. (2015). Limits to adaptation to interacting global change risks among smallholder rice farmers in Northwest Costa Rica. *Global Environmental Change*, *30*, 101–112. https://doi.org/10.1016/j.gloenvcha.2014.11.002

Yang, L., Liu, M., Lun, F., Yuan, Z., Zhang, Y., & Min, Q. (2017). An analysis on crops choice and its driving factors in agricultural heritage systems-A case of Honghe Hani rice terraces system. *Sustainability*, *9* (1162), 1162–1118. https://doi.org/10.3390/su9071162

Yoder, R. (1994). *Locally managed irrigation systems: Essential tasks and implications for assistance, management transfer, and turnover programs*. International Water Management Institute.