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The Effects of Changing Climate and Market Conditions on Crop Yield and Acreage Allocation in Nepal

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Received: 27 March 2018; Accepted: 20 April 2018; Published: 26 April 2018

Abstract: This study examines the impact of changing climate and product market conditions on crop yield and land allocations in Nepal. Zellner's seemingly unrelated regression approach is used to estimate the acreage and yield functions. The potential impact of price endogeneity on estimated parameters is corrected using an instrumental variable method. The results show that farm input prices and output prices play a crucial role in determining acreage allocation. While the variation in daily temperature during planting season affects acreage allocations for all crops except wheat, the total precipitation is critical for upland crops, particularly for millet. Literacy rate and the number of rainy days significantly affect yield for most crops. Moreover, the rising winter warming is enhancing wheat and potato yields. The results also show that a ten percent decrease in the number of rainy days during the growing season is likely to reduce yields for rice, maize, and wheat by 4.8, 1.7, and 0.8 percent, respectively.

Keywords: socioeconomic conditions; market prices; crop yield; land allocation; climate change

1. Introduction

The primary objective of this study is to evaluate the impact of changing climate and market conditions on agricultural production in Nepal. Understanding effects of global warming on agriculture are important because the Intergovernmental Panel on Climate Change (IPCC) report indicates that the Hindu-Kush Himalayan (HKH) region, where Nepal is located, is one of the hotspots for climate change [1–3]. The rate of change in temperature in HKH is expected to be significantly higher than the global average, particularly at higher elevations [2,4]. Other regional studies also show that the warming trend is changing rainfall pattern in volume as well as the number of rainy days in the region [5–8]. There is also a growing concern that global warming-induced changes in weather patterns and the depletion of ice fields, which is the primary source of fresh water for the region, are likely to have devastating impacts on many aspects of livelihoods including farm production [9–14].

Climate change affects agricultural production directly by altering the crop growth and production environment (e.g., temperature and precipitation) and indirectly by influencing total crop production, market supply, and demand conditions [15–18]. Since it is possible to mitigate some of these impacts by adopting new technologies, changing input combinations, and modifying cultivation practices, it is critical to account for the potential response of producers while measuring the effect of climate change on agriculture [13]. Furthermore, farm-level production decisions are affected by many other factors including access to production resources, uncertain market demand, and other socioeconomic conditions. These decisions become much more complicated and risky, when farm operators have inadequate information, are illiterate, have limited or no access to modern inputs such as farm equipment and machinery, financial resources, chemical fertilizer, and irrigation facilities [19–25].

Neumann et al. (2010) analyzed the global yield gap for major field crops and observed that access to production inputs such as irrigation; labor, land (slope), and other market resources considerably affect crop production efficiency. On the other hand, Schlenker and Roberts (2009) used more disaggregated county-level panel data to evaluate the impact of climate change and found a nonlinear relationship between daily temperature during the growing season and crop yield [17]. Roberts et al. (2012) further substantiate the nonlinear impact of climate on crop yield using various agronomic measures of weather variables [26]. Miao et al. (2016) also used similar panel data from the U.S. to examine the impact of both input and output market prices and weather variables on crop yield and acreage allocations. They found that the corn price affects both acreage allocation and corn yield. Moreover, weather effects, which was measured as a variation in rainfall and temperature, can reduce corn yield by seven to forty-one percent depending on the type of climate change scenario used in the analysis.

In general, the existing literature shows that global warming is increasing temperature, modifying rainfall pattern (in both time and space domains), and increasing the frequency as well as the intensity of extreme weather events [8,27,28]. Since temperature and precipitation are crucial factors for plant growth and development, climate change is likely to have a significant impact on agricultural production in the HKH region, including Nepal. In this light, this study focuses on the effects of climate change on five major field crops—rice, maize, wheat, millet, and potatoes—that are widely produced and consumed throughout the country.

Rice, maize, wheat, and millet are the top four staple food crops produced in Nepal and constitute nearly 100 percent of the total cereal crop production in the country [29]. In terms of calories, these four crops represent more than 90 percent of total food energy produced in Nepal [30]. On average, rice and maize together contribute 58 percent (40 percent for rice and 18 percent for corn) of the total daily calorie intake [31,32]. Moreover, most annual crop rotations in Nepal involve producing two to three crops from the same piece of land. Almost all of the rotations include more than one of the four crops and rising demand for them has increased the cropping intensity (i.e., total production acreage of rice, maize, wheat, millet, and potatoes/total arable land available in Nepal) from 0.96 in 1961 to 1.74 in 2014.

Consistent with the literature, this study incorporates the impact of climate change on agricultural production using historical average daily temperatures, the number of rainy days, and precipitation data [17,33]. Also, the effects of the growing proportion of educated labor force, changing market prices, expanded access to chemical fertilizer, increasing per capita energy use, and evolving agricultural education and extension services on yield and crop acreage are also assessed. Moreover, we evaluate linear as well as nonlinear relationships among the variables of interest using seemingly unrelated regression approach. The empirical results show that both market prices and weather variables have a significant impact on crop production in Nepal.

2. Method

2.1. Conceptual Framework: Factors Determining Crop Yield and Acreage

Agricultural production functions are generally specified as a mathematical relationship between various inputs (such as labor, capital, fertilizer, farm management, and other tillage practices used for producing the crop) and the final output generated per unit of land (e.g., acre or hectare). The production relationship is also likely to be affected by various external factors including existing socioeconomic conditions and changing the climate [25,33,34]. These external factors affect crop production by changing farm operators' motivation to produce a particular crop (e.g., by altering input or output prices) or by modifying the production environment that promotes or inhibits plant growth [33,35].

The average daily temperature and precipitation are the two primary climate-related variables that affect plant growth and crop yield [16]. Although more than fifty percent of the production acreage, particularly for rice in Nepal, is currently irrigated, rainfall provides a substantial portion of water for most crops [36–39]. Moreover, the country's rugged topography makes it difficult to expand irrigation facilities further, particularly in hill and mountain regions [39]. For these reasons, it is vital to understand the potential changes in temperature and rainfall patterns induced by global climate change on crop yield and acreage allocations.

2.2. Impact of Education and Agricultural R&D (Research and Development)

Knowledge (education) and access to technical know-how (e.g., crop/farm management training, market information, and crop research and development) play crucial roles in determining the farm operator's ability to manage farm activities optimally [32,40]. Since both are latent variables that are not readily measured, most studies use farm operator's education and various indices measuring the level of investment in agricultural research and development programs as proxies for knowledge and access to technical know-how, respectively [20,41]. In general, knowledge and technical know-how are positively related to crop yield because better educated and well-connected (with markets and information system) farm operators are more efficient in managing their operations. However, the impact of these variables on crop acreage is unclear.

Since this study uses national annual time series data and information on agricultural extension and training programs are not available, we use yearly literacy rates to measure education and total yearly foreign development aid (calculated as the total development assistance/arable land) to measure investments in agricultural research and development. The assumption in utilizing foreign assistance as a proxy for investment in agricultural research and development (technical know-how) is based on the observation that the majority of agricultural development programs in Nepal (e.g., crop breeding, variety development, irrigation, rural development, and other integrated watershed management projects) are funded through foreign aid. Objectives of these aid-funded agricultural projects include increasing the target population's access to improved crop varieties, provide market information, and to offer extension education and training programs [42,43].

2.3. Impact of Technology on Agriculture

Continued innovations and advancements in crop production, harvesting, processing, distribution, and marketing technologies have radically changed most aspects of food production and consumption systems in developed and developing economies [44–46]. These technologies have made it possible for about two farm operators to produce enough food to feed more than one hundred people in the U.S. and other developed economies. Although the transfer of technology from developed to developing countries has been sluggish, the fundamental nature of farming is slowly changing globally [47,48]. For instance, most growers in Nepal are smallholders with their primary focus on subsistence farming [49]. However, they are learning about new farm management practices and adopting affordable production technologies (e.g., improved crop variety, sustainable tillage practices, modern inputs, crop rotation, rice planters, and mechanical harvesters). Since there is no widely accepted measure of farming technology, various proxies such as the number of tractors per acre, the percentage of the population using the internet, and per capita energy use are used [50–52]. However, we were not able to find consistent data on the number of tractors, crop planters, and harvesters, other potential variables except for per capita energy use. Therefore, we use per capita energy use as a proxy for measuring the impact of technology on crop yield and acreage allocation. Since different techniques affect production efficiency differently, it is difficult to determine its relationship with crop yield and land allocations a priori.

2.4. Measurement of Weather Variables

In general, global warming affects agriculture directly through its biophysical impact on crop growth, development, and yield and indirectly by changing producer's ability to adapt to varying production conditions and market demand situations. Since Nepal is in one of the highly vulnerable regions of the world, climate change impacts are likely to be more severe for both crop yield and the adjustment costs [40,53].

The existing literature provides some agronomic measures to link weather with crop growth and development. Most studies predict nonlinear relationships between weather variables and crop yield [17,26,33,34,54]. For instance, Roberts et al. (2012) use growing degree days (GDD), extreme heat degree days (HDD), and the vapor pressure deficit (VPD) to measure temperature and the total rainfall during crop growing seasons [26]. Consistent with previous studies [17,34], their results show a nonlinear impact of both weather variables (temperature and rainfall) on crop yield. Miao et al. (2016) use GDD, GDD^2, HDD, and monthly temperature deviations for each month from March to August to measure temperature and monthly precipitation for the growing season to measure the impact of rainfall on corn and soybean yield in the US [33]. They also found a non-linear relationship between weather variables and crop yields.

Recent studies show that the number of rainy days is declining in many localities globally, including in HKH region [5,6]. Since a consistent supply of soil moisture throughout the growing season is critical for crop growth and development, particularly in rainfed farming systems, the number of rainy days are used as an alternative measure of rainfall in this study. Likewise, the weather condition during the planting season can also influence acreage allocation decisions of producers. Since most highland production acreage in Nepal is rainfed, limited soil moisture (or rainfall) during planting season would seriously jeopardize producers' ability to plant economically profitable crops.

2.5. Empirical Models

We use two separate models for each crop analyzed in the study to examine effects of weather variables on crop yield and acreage allocation. Consistent with the existing literature, the yield function (Y_{it}) for crop i at period t is specified as:

$$\begin{aligned} Y_{it} = \alpha_i + \beta_{i1}P + \beta_{i2}Lit + \beta_{i3}Frt + \beta_{i4}Eng + \beta_{i5}Aid + \beta_{i6}Rn + \beta_{i7}Rn^2 + \beta_{i8}GDD \\ + \beta_{i9}GDD^2 + \beta_{i10}\sigma_{tm} + \beta_{i11}\sigma^2_{tm} + \varepsilon_i \end{aligned} \tag{1}$$

where Y_{it} = crop yield and i ranges from one to five representing five major food crops grown in Nepal (i.e., 1 = rice, 2 = maize, 3 = wheat, 4 = millet, and 5 = potatoes) and t refers to sample years from 1976–2014. The explanatory variables P, Lit, Frt, Eng, Aid, Rn, GDD, an σ_{tm} are the one period lagged crop prices, literacy rate, fertilizer application rate (Kg/Hectare), per capita energy use, development aid (foreign development aid/arable land), rainfall during production season (Rn), Rn squared (Rn^2), growing degree days (GDD), GDD squared (GDD^2), standard deviation of daily temperature (for growing season, σ), and variance of daily temparature (σ^2) respectively and β_i's are the set of unknown parameters to be estimated. The ε_i is a random error term.

Following White (2003) and Roberts et al. (2012), the growing degree days index for the crop production season is defined as GDD = sum (average daily temperature − base temperature). Since the weather data are in Fahrenheit, we use 50 °F as the base temperature for rice, corn, and millet; 46.4 °F for potatoes; and 41.9 °F for wheat [26,55]. The rainy days index is a count of the number of days with total recorded precipitation greater than 2.5 mm [5,6,56]. In this study, the number of rainy days is the total rainy days for crop growing season. Lastly, the variability measures of temperature are the aggregate variance and standard deviations of daily temperatures observed during the growing season.

The production seasons for the five significant crops analyzed in the study are defined as follows. The millet and rice production seasons range from June to November. Wheat and potato production seasons range from November to February and the corn season ranges from March to June [57–59]. Although there are significant variations in planting, growing, and harvesting dates between geographical and ecological regions of Nepal, these seasons are broad enough to cover the production window for most crops. One of the most common annual crop rotations on irrigated lowlands is spring maize-summer/fall rice-winter wheat [59].

Crop acreage allocation decisions are affected by many of the factors that influence crop choice, such as crop prices (P), farm operator's knowledge base (Lit: literacy or education), the cost of fertilizer

(*Fpx*: fertilizer price index), and investment in agricultural infrastructure (*Aid*: foreign development aid/arable land), rainfall (*Rain*), growing degree days (*GDD*) and the variation in average daily temperature (*Var*). We define:

$$A_{it} = \alpha_i + \beta_{i1}P + \beta_{i2}Lit + \beta_{i3}Fpx + \beta_{i4}Eng + \beta_{i5}Aid + \beta_{i6}Rn + \beta_{i7}Rn^2 + \beta_{i8}GDD + \beta_{i9}GDD^2 + \beta_{i10}\sigma_{tm} + \beta_{i11}\sigma^2_{tm} + \varepsilon_i \quad (2)$$

where all variables except for A_{it} (crop acreage in hectare) and *Fpx* (fertilizer price index) are defined as before. To maintain consistency with the yield model, we kept the same set of explanatory variables in both models, except for replacing the fertilizer quantity variable with a fertilizer price index. However, all weather variables were measured by using average daily temperature and rainfall data for two months during planting season. For instance, summer rice transplanting starts in mid-June and ends in July. Therefore, weather data for June and July are used to construct temperature and rainfall indices for rice planting season.

2.6. Model Estimation

Although the yield equations as specified in equation one are independent of each other and can be estimated separately, their error terms might be correlated because of contemporaneous factors. Some examples of these factors may include disease outbreak, cultivation practices, and nutrient management routines with effects that extend multiple seasons. For instance, heavy use of chemical fertilizer to produce summer/fall crops (e.g., rice) can deplete soil nutrients (soil organic matter) and significantly affect winter crop yield (e.g., wheat or potatoes). To account for these correlations, we estimate the crop yield and acreage functions simultaneously as two separate systems using Zellner's seemingly unrelated regression (SUR) model and determine whether the error terms of the five different yield (acreage) functions are correlated using the Breusch-Pagan test of independence [60].

Moreover, there is a significant gap between the time when farm operators make the decision to plant a crop and when they are ready to harvest and market the produce (e.g., about five months for rice and about three months for potatoes). Because of this gap, farmers have to make decisions based on expected prices rather than the observed prices. In the case of annual field crops, most studies address this issue by using a one period lagged output price or the current year futures price as a proxy for expected price. Miao et al. (2016) caution about using the lagged output price (or futures price) as an explanatory variable in crop yield and acreage allocation functions because it may cause endogeneity bias. In particular, they argue that factors such as autocorrelated price variables and market shocks with multiyear effects may make output prices correlated with error terms in yield and acreage functions. Robert and Schlenker (2013) and Miao et al. (2016) use weather and other crop inventory variables as instruments for prices and estimate yield and acreage functions using the instrumental variable approach. Consistent with these studies, we use weather variables as instruments for price and estimate model parameters using the instrumental variable method.

2.7. The Data Sources and Study Period

The dataset used in this study was generated using four different online sources. The annual series (1961–2014) of average crop yield, crop prices, and input price indices were downloaded directly from the Food and Agriculture Organization website (http://www.fao.org). The second set of annual time series data on literacy rate, foreign development assistance, and per capita energy use data were obtained from the World Bank database (https://data.worldbank.org/). Monthly rainfall data are from the Climate Research Unit (https://crudata.uea.ac.uk/cru/data/hrg/) TS3.10 Dataset [61]. The second set of weather data, the daily average temperature, was downloaded from the National Centers for Environmental Information website (https://www.ngdc.noaa.gov/). Missing observations for crop price and weather variables resulted in the final dataset used in this study covering information from 1976 to 2014.

3. Empirical Results

3.1. Summary Statistics

The summary statistics for variables used in the regression analysis are presented in Table 1. On average, the total arable land in Nepal was about 2.3 million hectares during the sample period (1976–2014). In terms of acreage allocations, the major crops produced during this period include rice (45.3%), maize (23%), wheat (18.6%), millet (6.8%), potato (3.4%), sugarcane (1.3%), barley (0.9%), jute (0.6%), and tobacco (0.2%). Because of their higher annual production acreage, importance in Nepali diet, and data availability, this study focuses on the first five major food crops. The five crops together represent about 97% of the total cropped area and provide more than 90 percent of the total food energy (Kcal/year) produced in Nepal annually.

Table 1. Summary Statistics for Variables Included in the Regression Analysis.

Variable Description	Mean	St. Dev.	Min	Max
Rice Yield (Metric Ton/Hectare)	2.40	0.46	1.45	3.39
Maize Yield (Metric Ton/Hectare)	1.77	0.31	1.33	2.50
Millet Yield (Metric Ton/Hectare)	1.06	0.08	0.91	1.17
Wheat Yield (Metric Ton/Hectare)	1.63	0.42	1.04	2.50
Potato Yield (Metric Ton/Hectare)	9.12	2.97	5.10	13.74
Current Price of Rice (NRS/Metric Ton)	8.20	6.69	1.24	25.26
Current Price of Maize (NRS/Metric Ton)	8.33	6.76	1.63	25.92
Current Price of Millet (NRS/Metric Ton)	8.65	7.01	1.59	29.05
Current Price of Wheat (NRS/Metric Ton)	8.71	6.64	1.77	25.81
Current Price of Potato (NRS/Metric Ton)	9.01	7.37	1.66	27.22
Rice Acreage (1000 Hectares)	1434.04	105.57	1254.24	1560.04
Maize Acreage (1000 Hectares)	727.59	154.51	432.34	928.76
Millet Acreage (1000 Hectares)	214.12	60.41	121.13	278.03
Wheat Acreage (1000 Hectares)	588.28	130.51	328.57	767.50
Potato Acreage (1000 Hectares)	108.79	48.25	49.58	205.73
Energy Use (Kg of Oil Equivalent per capita)	329.4	27.8	301	389
Adult Literacy Rate (%)	34.9	14.0	21	60
Net Foreign Aid/Arable Land (NRS/Hectare)	187.3	109.1	22	420
Fertilizer Price Index	138.4	73.5	66	373
PS Rain (in mm): June-July (rice/millet season)	486.7	88.0	312	647
March-April (maize)	105.8	39.5	24	180
November-December (wheat/potato)	30.0	28.6	1	128
GS Rain (in mm): June-October (rice/millet)	990.7	125.3	777	1264
March-June (maize season)	382.9	67.6	256	530
December-January (Wheat/Potato)	37.8	25.9	1	127
PS Temperature (in F): June-July (rice/millet)	74.9	1.6	72	79
March-April (maize)	65.3	3.1	58	73
November-December (wheat/Potato)	55.6	2.4	50	61
GS Temp (in F): June-October (Rice/Millet GDD)	72.9	1.5	70	76
March-June (maize GDD)	69.5	2.3	65	76
December-January (Wheat/Potato GDD)	51.2	2.2	46	56
PS σ_{ptm}: June-July (rice/millet)	0.8	0.6	0	3
March-April (Maize)	4.7	2.1	0	12
November-December (Wheat/Potato)	4.8	1.2	2	7
GS σ_{ptg}: June-October (Rice/Millet)	3.4	0.9	1	6
March-April (Maize)	5.9	1.3	4	9
November-December (Wheat/Potato)	1.9	1.3	0	5

Note: PS = planting season; GS = growing season; Temp = temperature; and NRS = Nepalese Rupees. The average temperature is based on monthly Climate Research Unit TS3.10 Dataset [61]. The GDD and temperature standard deviations (σ) are based on daily observations recorded in the Tribhuvan International Airport in Kathmandu, Nepal (data from National Center for Environmental Information website: https://www.ncei.noaa.gov/).

The total production acreage, as well as the average yield for four of the five crops (except for millet), increased substantially during the study period. The annual yield growth was highest for potatoes (3.40%), followed by wheat (2.87%), rice (2.04%), maize (0.96%), and millet (−0.03%). The growth in crop acreage came mainly from the steady increase in cropping intensity—primarily from winter (potatoes 7.34% and wheat 3.32%) and spring (maize 2.78%) crops. Since these are major staple crops with stable demands, their prices have also been steadily rising over time. The average annual price increase is highest for rice (49.72%), followed by millet (44.29%), potatoes (39.47%), maize (38.23%), and wheat (34.81%).

Similarly, substantial annual growth in the literacy rate (4.87%), per capita energy use (34.63%), and net foreign aid (45.42%; measured as net foreign aid/arable land) were observed during the study period. These enhancements in producers' educational level, energy use, and net development expenditure might be partly responsible for the increasing cropping intensity and crop yields over time. Moreover, increasing use of chemical fertilizers (about 22% per annum) and other improved cropping practices likely have enhanced the crop yield.

The climate data analyzed in this study show that the weather pattern has changed significantly during the 39 years (1976–2014) study period. A simple trend (t) analysis of annual averages for daily low temperature (L), high temperature (H), and average temperature (A) was conducted to examine the changes in annual average daily temperature. The results show that low, high, and average temperatures increased by 0.0375 °C, 0.0332 °C, and 0.0351 °C, respectively. We also search for a potential trend in rainfall patterns, and empirical results showed that the trend coefficients for both total annual rainfall (*Rn*) and the number of rainy days in a year (*Rd*) had negative signs indicating a declining trend.

3.2. Yield Model Results

The yield functions (Equation (1)) for rice, maize, wheat, millet, and potatoes were simultaneously estimated using Zellner's seemingly unrelated regression (SUR) model to account for the potential impact of contemporaneous correlation among error terms on parameter estimates and the results are displayed in Table 2. The SUR estimators are more efficient than ordinary least square (OLS) particularly in estimating standard errors. Moreover, SUR is a systems approach that allows conducting joint tests to evaluate the impact of explanatory variables across the equations.

The estimated Breusch-Pagan (BP) test statistic, which is distributed as χ^2 with ten degrees of freedom, is 32.75. The critical value for $\chi^2_{(10,\ \alpha=0.01)}$ is 23.21, so the estimated BP statistic is significant at less than one percent level ($p < 0.01$). Thus, the residuals of the yield functions are contemporaneously correlated (i.e., they are not independent, which in turn indicates that SUR parameters are more efficient than OLS). Moreover, the R^2 values for the individual crop yield models range from 0.41 (for millet) to 0.97 (for potatoes) indicating an adequate explanatory power of the models and the χ^2-values for all five models are highly significant, at ($p < 0.01$), further supporting the good fit of the estimated models.

Although some of the recent literature reports a significantly positive impact on output prices on crop yields (e.g., Miao et al., 2016), only two out of five price coefficients are positive, and only one of them is statistically significant (for maize) in this study. Since most crop producers in Nepal are subsistence farmers with inadequate access to modern inputs, market information, and other yield-enhancing alternatives, insignificant price effects on crop yield are consistent with the general state of agriculture in the country.

The total annual import of chemical fertilizer per hectare was used as a proxy to measure the impact of modern inputs (fertilizer) on crop production because consistent time series data on input prices and application rates are not available. Chemical fertilizers are primarily used to enhance crop yield, but the estimated results show that only two fertilizer coefficients are statistically significant and they carry opposite signs. Fertilizer has a significantly positive impact on rice yield, but it has a negative impact on maize. A possible explanation for the contradictory results might be a potential difference in fertilizer application rates between rice and other relatively low-value crops including maize and millet. Since most lowland annual crop rotations in Nepal involve planting rice during the summer followed by winter (potatoes or wheat) and spring (maize) crops [59,62,63], heavy use of fertilizer during rice cultivation may reduce soil nutrients available to the subsequent crops and have a negative impact on their yields.

Table 2. Seemingly Unrelated Regression (SUR) Parameters for Crop Yield Models.

Variable	Rice	Maize	Wheat	Millet	Potato
Intercept	−55.4705	33.7946 *	−16.6594 *	52.9434	38.6151
	−(1.09)	(2.01)	−(2.02)	(1.39)	(0.71)
Price	−0.2275	0.4778 **	0.1086	−0.0534	−0.5648
	−(1.10)	(5.38)	(1.08)	−(1.02)	−(1.29)
Fertilizer	0.0538 *	−0.0601 **	0.0113	−0.0022	−0.0005
	(2.37)	−(4.85)	(1.02)	−(0.24)	−(0.01)
Literacy Rate	0.0848	0.1195 **	0.0739 *	0.0617 *	1.4190 **
	(1.29)	(3.01)	(2.33)	(2.45)	(5.86)
Foreign Aid	0.0164 *	0.0051	−0.0024	0.0037	0.0778 **
	(2.16)	(1.44)	−(0.65)	(1.58)	(3.44)
Energy Use	0.1003 *	−0.0684 *	0.1121 **	−0.0158	0.1408
	(2.13)	−(2.26)	(4.45)	−(0.85)	(0.79)
Rainfall (*Rn*)	1.0659 *	0.4298 *	1.9949 **	0.1573	3.3510
	(2.23)	(2.20)	(4.93)	(0.76)	(1.12)
Rainfall Squared	−0.0078 *	−0.0065 *	−0.1954 **	−0.0015	−0.4074
	−(2.21)	−(2.15)	−(4.77)	−(0.75)	−(1.35)
GDD	0.0044	−0.0051	−0.0149 *	−0.0376	−0.1185 **
	(0.16)	−(0.75)	−(2.45)	−(1.05)	−(2.73)
GDD Squared	0.0000	0.0000	0.0000 *	0.0000	0.0001 **
	−(0.17)	(0.97)	(1.93)	(1.03)	(2.98)
σ_{tm}	−0.9067	−0.8986	−3.4348 **	0.2719	−11.9045
	−(0.96)	−(0.43)	−(2.99)	(1.04)	−(1.38)
$\sigma^2{}_{tm}$	0.0633	0.0595	0.4089 **	−0.0262	1.1450
	(1.08)	(0.41)	(3.06)	−(1.19)	(1.14)
R^2	0.90	0.93	0.97	0.41	0.97
χ^2	337.09	528.95	1343.30	31.52	1140.70

Note: *t*-Values are in parenthesis. GDD refers to growing degree days during crop growing season (e.g., March and April for maize). The yield functions were estimated simultaneously using Zellner's seemingly unrelated regression model. The $\chi^2{}_{(10)}$ value for the Brueusch-Pagan test of independence is 32.75 is significant at one percent level (the critical value for $\chi^2{}_{(10,\ \alpha=0.01)}$ is 23.21). **, * Denote parameter significance at one and five percent level, respectively.

Since knowledge and access to technical know-how are crucial factors in determining farm productivity, the literacy rate and foreign development assistance (net overseas development assistance/arable land) were used as proxies for measuring the impact of knowledge and technical know-how about farming on crop yield. Our logic in using foreign development assistance as a proxy for technological know-how is based on the observation that most agricultural extension, education, and infrastructure development projects in Nepal are funded through foreign development assistance [43]. Some of these activities include large-scale irrigation systems, rural development programs, and integrated watershed management projects. Moreover, most of these programs include agricultural education, research and extension components, and farmer training programs [43].

The empirical results show that both literacy rate and foreign development assistance have the most positive impact on crop yield. In particular, all five literacy coefficients carry a positive sign and four of them are statistically significant ($p < 0.05$). Nepal made substantial education improvements during the study period, and the results show that the investment in education has had a significantly positive impact on crop yields. On the other hand, most coefficients of foreign assistance variable (except for wheat) are positive, and they are statistically significant for rice and potatoes ($p < 0.05$). These results indicate that aid induced increases in access to modern inputs and technical know-how (e.g., agricultural education, extension, and training) have contributed to some degree in increasing rice and potato yields.

Farming machinery such as tillers, planters, harvesters, and threshers play crucial roles in reducing production cost and enhancing farm productivity [20,21]. Some of the more widely used agricultural machines in Nepal include cultivators (e.g., handheld tiller and tractor mount cultivators), planters, harvesters, and threshers but reliable time series data on the supply and utilization of these farming technologies for the study period were not available. Therefore, we used per capita energy consumption as a proxy to measure the extent of farm technology used over time in Nepal. The results show that increasing use of farming technologies as measured by per capita energy use had a significantly positive impact on rice and wheat yield but negative impact on maize yield. One of the explanations for the opposing sign of technology coefficient might be the inherent difference in the level of mechanization between these three crops and the topography where they are primarily grown. Rice and wheat harvesting and processing technologies are more accessible than maize because maize harvesters are massive, cost more, and require more training to operate. Moreover, rice is primarily grown in Tarai (plains) and inner valleys that make it easier to access and adopt these farming technologies.

Historical data on rainfall, temperature (i.e., growing degree days), and variation in average daily temperatures served as proxies for climate variables. The results show that all three variables have a statistically significant impact on at least one crop. Overall, rainfall appears to be the most crucial weather variable in determining crop yield in Nepal. The cumulative rainfall received during the growing season has a nonlinear (quadratic) and significantly positive impact on rice, maize, and wheat yields but not on millet and potatoes. Millet is one of the drought-resistant crops grown in Nepal, mostly in uplands under the rainfed condition, and it seems to do well even when the rainfall is low. On the other hand, potatoes are mostly grown on lands with some access to irrigation during winter immediately after the rice is harvested. The top three cereal crops that contribute more than 86 percent of the total food calorie produced in Nepal are highly sensitive to climate-induced change in rainfall pattern.

The rising temperature has a significant impact primarily on the yields of winter crops—wheat and potatoes. In both cases, the temperature has a non-linear u-shaped relationship (i.e., +GDD and $-\text{GDD}^2$) with crop yield indicating that the recent trend in winter warming is likely to boost wheat and potato yields. These results are consistent with the literature that shows winter warming is enhancing wheat and other winter crop yield in the HKH region and other parts of the world [4,64–67]. Additionally, wheat is also sensitive to variations in temperature. These results show that all three weather variables used in the model (rainfall, temperature, and variation in temperature) have significant impacts on crop yield.

3.3. Acreage Response Model Results

The empirical parameters for the estimated acreage allocation functions (from equation 2) are presented in Table 3. The model fit indices for the acreage functions are relatively better than for the yield models. In particular, the R^2 values range from 0.80 (rice) to 0.97 (potatoes) indicating a reasonably high explanatory power of the estimated models. Similarly, the χ^2 values range from 159.76 (rice) to 1565.42 (potatoes), and all of them are highly significant ($p < 0.01$) indicating a better fit of the models. Also, the statistics related to the Breusch-Pagan test of independence are highly significant ($p < 0.01$) implying that the error terms of all five acreage allocation functions are correlated and should be estimated jointly as a system of equations to account for the contemporaneous correlations.

The price coefficients on all five acreage functions are highly significant and carry positive signs implying that producers pay close attention to expected crop prices while making land allocation decisions (Miao et al., 2016). The estimated elasticity is highest for millet (0.58) followed by wheat (0.39), maize (0.37), potatoes (0.34), and rice (0.15). These elasticity measures fall within the range reported in several previous studies [33,68–71]. Moreover, coefficients of the fertilizer price index are negative for all five acreage functions and are significant for rice, maize, and potatoes. These results together indicate that growers take into account not only output prices but input prices as well when making their acreage allocation decisions. In particular, growers are likely to allocate more acreage to crops that are expected to yield higher prices and vice versa. On the other hand, growers are likely to reduce crop acreage if chemical fertilizer prices increase substantially.

Table 3. Acreage Model Parameters.

Variables	Rice	Maize	Wheat	Millet	Potato
Intercept	−25.3305	10.7007 *	12.6748	132.3613	49.1120 *
	−(0.33)	(2.25)	(1.30)	(1.00)	(2.97)
Log(Output Price)	0.1479 **	0.3733 **	0.3933 **	0.5769 **	0.3375 **
	(5.02)	(7.56)	(6.37)	(10.97)	(5.03)
Fertilizer Price Index	−0.0003 *	−0.0004 *	−0.0002	−0.0002	−0.0012 **
	−(2.17)	−(2.09)	−(1.05)	−(0.79)	−(3.52)
Literacy Rate	−0.0045 **	−0.0033	−0.0028	0.0002	0.0063 *
	−(2.80)	−(1.53)	−(1.10)	(0.06)	(1.88)
Log(Foreign Aid)	−0.0102	0.1165 **	0.1072 **	−0.0126	0.1210 **
	−(0.51)	(3.96)	(3.08)	−(0.35)	(3.03)
Log(Energy Use)	0.1983	−1.1694 **	−1.2255 **	−2.4002 **	0.8217
	(0.75)	−(3.08)	−(3.40)	−(5.02)	(1.47)
Log(Rainfall)	0.8108	0.0932	−0.0092	8.6890 **	0.0174
	(0.49)	(0.47)	−(0.50)	(3.06)	(0.46)
Log(Rainfall^2)	−0.0642	−0.0105	0.0017	−0.7179 **	−0.0063
	−(0.47)	−(0.47)	(0.45)	−(3.09)	−(0.84)
Log(GDD)	9.3746	1.3476	0.9984	−37.7003	−13.0917 **
	(0.44)	(1.09)	(0.37)	−(1.04)	−(2.83)
Log(GDD^2)	−0.6306	−0.0998	−0.0764	2.5895	0.9925 **
	−(0.44)	−(1.08)	−(0.37)	(1.05)	(2.84)
Log(σ_{tm})	−0.1419 *	1.3472 **	0.7609	−0.3626 **	−3.5772 *
	−(1.93)	(4.65)	(1.02)	−(2.78)	−(2.53)
Log(σ_{tm} Squared)	0.0665 *	−0.3965 **	−0.2573	0.1222 *	1.1101 *
	(2.19)	−(4.34)	−(1.12)	(2.32)	(2.56)
R^2	0.80	0.96	0.96	0.96	0.97
χ^2	159.76	940.40	1036.96	1082.98	1565.42

Note: *t*-Values are in parenthesis. All weather variables are measured for planting season (e.g., temperate during June and July for rice). The acreage allocation functions were estimated simultaneously using Zellner's seemingly unrelated regression model. The $\chi^2_{(10)}$ value for the Brueusch-Pagan test of independence is 58.33 is significant at one percent level (critical value for $\chi^2_{(10,\,\alpha=0.01)}$ is 23.21). **, * Denote parameter significance at one and five percent level, respectively.

As with the yield equations, the literacy rate and foreign development assistance are used in the acreage response models to evaluate the impact of knowledge and technical know-how on land use decisions. The results show that the effect of the literacy rate on acreage allocation is not as crucial as on crop yield. Only two literacy rate coefficients are significant (on the rice and potatoes equations) and carry opposite signs. Although these coefficients are contradictory, they may reflect the emerging trend in the Nepalese labor market, particularly among younger generations who tend to be more educated than their parent's generation. Since agriculture is relatively a less preferred profession, younger generations are seeking employment in non-agricultural sectors of the economy as indicated by the negative sign of all three major crops – rice, maize, and wheat. On the other hand, the impact of foreign development assistance has a significantly positive effect on acreage allocation particularly for maize, wheat, and potatoes.

Weather variables during the planting season are used to examine the impact of climate change on acreage allocation. The results show that among three climate variables used in the study, variation in temperature is more critical than rainfall and the average temperature for making acreage allocation decisions. While the total precipitation significantly affects millet and average temperature affects potatoes, the variation in daily temperature affects all of the crops except for wheat (a winter crop).

Since drought during the planting season is one of the critical factors that limit producers' ability to plant crops, these results are consistent with the observations made in previous studies [14,19].

4. Conclusions and Policy Recommendations

4.1. Conclusions

We examined the effects of market prices, education, technical know-how (development assistance), technology adoption (energy use), and three climate variables (rainfall, average daily temperature (i.e., GDD), and variation in average daily temperature) on crop yield and acreage allocations in Nepal. The model fit indices (R^2 and χ^2 values) are relatively high indicating the good explanatory power of the analytical models. Although not all estimated parameters are significant, joint tests show that the aggregate impact of the variables included in the SUR system is statistically significant indicating their crucial role in determining crop yield and acreage allocations. Moreover, the Breusch-Pagan tests of independence show that the error terms of both the crop acreage models and the yield models are correlated and should be estimated as a system.

Overall, the yield model results show that education (literacy rate) and climate variables (particularly rainfall patterns) are the most critical determinants of crop yields in Nepal. The rising literacy rate has a positive impact on yield of all five crops analyzed in this study. This finding is consistent with the argument that continuing investment in human capital formation (education) enhances labor productivity. Likewise, rainfall (measured as the number of rainy days during the growing season) has a statistically significant and nonlinear relationship with yield particularly for rice, maize, and wheat. Moreover, the empirical results show that, on average, a 10 percent decrease in the number of rainy days would reduce rice, maize, and wheat yields by 4.8, 1.7, and 0.8 percent, respectively.

The growing degree days has a significant and nonlinear (positive in aggregate) impact on both winter crops (wheat and potatoes). Similarly, the variation in average daily temperature has a statistically significant effect on wheat yield. Together these results show that global warming-induced increases in the mean and standard deviation of average daily temperature is likely to increase wheat and potato yields in Nepal. These findings are also consistent with recent observations that rising autumn and winter temperatures are boosting crop yields in other parts of the Himalayan region and globally [4,64,67].

The acreage function results show that market prices (for both inputs and output) play a crucial role in determining land allocation decisions. Producers' tend to increase crop acreage when the output price rises and reduce it when input prices rise indicating their responsiveness to changes in market conditions. On the other hand, the rising literacy rate has a relatively small impact on crop acreage and even carries a negative sign in the rice equation. Among climate variables, variation in the daily temperate plays a prominent role in determining acreage allocations, particularly for rice, maize, millet, and potatoes. Moreover, rainfall has a significant impact on millet, and average temperature has a considerable effect on potato acreage.

To sum up, the grower's knowledge (literacy rate) and rainfall pattern play a crucial role in determining crop yield in Nepal. Increased investment in human capital related to crop production knowledge, technical know-how, and improved access to modern inputs including affordable irrigation technologies are likely to be most effective in enhancing crop productivity. Improved access to market resources (price information, transportation infrastructure, and farming technologies) and weather information are likely to make producers more responsive to changing market and weather conditions in Nepal.

4.2. Policy Recommendations

We can draw following four significant policy implications for reducing the impact of climate change and enhancing farm productivity from our empirical results. (1) Increase investment in agricultural research and development programs with particular focus on developing drought-tolerant high yielding crop varieties that are suitable for different ecological and climatic zones. An introduction of new climate-smart crop varieties can help in reducing the overall impact of climate change on farming households. (2) Enhance agricultural knowledge and technical know-how of farm operators by providing educational, training, and extension opportunities. In addition to better management of farm operation, the highly skilled workforce can also help Nepal in transitioning from subsistence farming to a commercially viable agricultural production system. (3) Develop an efficient mechanism to provide prompt access to weather information, input and output market prices, climate-smart production practices, and risk management options to all farm operators. Better access to reliable information on weather, market prices, production practices, and risk management options is essential for efficient operation of an agribusiness firm. (4) Enhance producer's access to modern inputs and other crucial production resources such as climate-smart crop varieties, soil nutrients (organic and chemical fertilizers), irrigation facilities, fertile land, and farm equipment (e.g., planter, harvester, and food processing and storage facilities). Most farms in Nepal are too small to be commercially viable units of production (less than 1.0 ha.). An explicit legal provision for consolidating individual plots and expanding farm size would make it possible for farms to adopt new technologies, access financial resources to purchase farm equipment, gain market power in product markets, and enhance farm profitability.

4.3. Limitations

Aggregate information on crop yields, production acreage, market prices, and weather from various sources are used for the empirical analysis presented in this study. Reliable data on some of the critical variables such as daily temperature, rainfall, grower's education, training, and technical know-how, investments in agricultural research and development, input applications, and farm technologies are not available. To account for the impact of these variables on crop yield and acreage allocations, a number of proxy variables were used in their place. Moreover, other factors such as a change in population dynamics (e.g., population growth and migration) and a shift in producers' preference for cash crops (e.g., coffee, cardamom, and pulses, etc.) may significantly impact crop acreage as well as crop yield. However, because of data limitation, we were not able to control for these factors in the model. Therefore, we caution readers about these limitations and their potential impact on estimated results.

Acknowledgments: This research was supported in part by the New Mexico Agricultural Experiment Station and USDA Hatch funding.

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

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