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Factors affecting maize, rice and wheat yields in the Koshi River Basin, Nepal

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Abstract

Crop yield is mainly affected by climatic factors such as temperature and precipitation. Besides these factors, improved seeds, irrigation access, and fertilizers also affect yield. In the present study, we collected crop yield data for major crops such as maize, rice, and wheat from the Koshi River Basin, Nepal. We investigated the yield trends over 30 years (1987–2016) and related the yields with climatic factors (temperature and precipitation). We also investigated the trends in the use of improved seeds, irrigation access, and fertilizer use in our study area. Results showed that there was an increase in yield of maize, rice, and wheat over 30-year period. Maize yield slightly increased with increasing average temperature. Rice yields significantly decreased with increasing temperature and precipitation, whereas wheat yield increased with increasing the diurnal temperature range. The present study suggests that future yields of maize, rice, and wheat will be affected by the increasing temperature than precipitation in the Koshi River Basin, Nepal.

Key words: Agriculture products, GLMM, Precipitation, Temperature, Yield variation

1. Introduction

Climate change is a key driver of agricultural production, as it affects precipitation and temperature patterns (Pachauri *et al.*, 2008). The extreme events caused by climate change have been studied on a global scale (Alexander *et al.*, 2006). The impact is severe for the rural livelihoods that are engaged in subsistence agriculture because of increasing water stress, diseases, and other climate induced water hazards and extremities such as drought (Paudel Khatiwada *et al.*, 2017).

The Intergovernmental Panel for Climate Change (IPCC) reported that the average temperature increased between 0.15°C to 0.30°C per decade for the 1990 to 2005 period. It was 0.75°C to 0.99°C for 2006–2015, and it has been estimated to be 0.8°C to 1.2°C for the 2030–2052 period (IPCC, 2018). There is a 66% to 90% chance that the Asian monsoon precipitation will vary with increasing greenhouse gases concentration in the atmosphere. This chance of intense precipitation is projected to increase in the 21st century (Folland, 2001; IPCC, 2007). A significant increase in the number of annual hot days and warm nights and a decrease in the number of rainy days were observed in the South East Asia and South Pacific region (Manton *et al.*, 2001). Over 70% of the region experienced fewer wintry nights annually, and a significantly increased amount of precipitation.

Nepal is a topographically diverse country; mountains cover 35%, hills cover 42%, and flat lowlands (commonly called "Terai" in Nepali language) cover 23% of its total area. Over 65% of Nepal's population depends on agricultural activities for livelihood, which contributes to about 32% of its national gross domestic product (Ministry of Agricultural Development, 2015). Different varieties of crops are grown in Nepal. Rice, wheat, and maize are the most common and important crop species. Rice covers 45%, wheat covers 18%, and maize covers 20% of the total cultivated area in Nepal (Gautam, 2008; Malla, 2008). Cropping patterns vary according to the agricultural zones, from high mountains to the low Terai. Rice can be cultivated once a year from 1000 m to 2200 m above sea level and twice a year below 1000 m (Bhatt *et al.*, 2014). Similarly, maize can be grown up to 2500 m and wheat up to 3000 m (Haffner, 1984; Bhatt *et al.*, 2014). Rice production twice a year in places such as Terai and some parts of a hilly region, where there are proper irrigation facilities.

Few studies in Nepal showed that there is an erratic pattern of fewer rainy days with a high intensity of precipitation with

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no effect on the total amount of annual precipitation (Shrestha *et al.*, 2000; Baidya and Karmacharya, 2007) causing prolonged drought and flooding. Similarly, daytime temperatures increased by 0.06℃ to 0.12℃ per year (Shrestha *et al.*, 1999). According to the Representative Concentration Pathway (RCP), there will be an increment in precipitation in Nepal from 2.1% (2016–2045) to 7.9% (2036–2065) for RCP 4.5 scenario, and from 6.4% to 12.1% for RCP 8.5 scenario compared to the reference period from 1981 to 2010. Similarly, the temperature will increase by 0.92℃ to 1.3℃ for RCP 4.5 and 1.07℃ to 1.82℃ for RCP 8.5 in the same period (Ministry of Forests and Environment, 2019). The IPCC B2 Special Report on Emissions Scenario (B2 SRES), also mentioned that there will be an increment in mean temperature of 1.2℃ and 3℃, by the year 2050 and 2100 respectively (Agrawala *et al.*, 2003).

Any climatic changes in different topographic zones may affect the cropping pattern (Pachauri *et al.*, 2008). Increase in temperature in Terai of Nepal may harm the yield of certain crops in this region, but may be favorable for the hill and mountain zones of the country, as these zones have relatively lower temperatures under normal conditions (Malla, 2008). Crop yields also increase with improved seeds (Pandey and Velasco, 2002; Karki *et al.*, 2010; Chhetri *et al.*, 2012; Paudel, 2012; District Agriculture Development Office, 2016a), fertilizers (Bhatta and Neupane, 2010; Shrestha, 2010; Henderson *et al.*, 2016), and irrigation (Bahadur *et al.*, 2015; Dahal *et al.*, 2015; DADO, 2016b; Paudel, 2016).

The Koshi River Basin (KRB), Nepal is home to 13.7 million people and livelihoods of people in this basin are mostly depended on agriculture (Neupane *et al.*, 2015; Hussain *et al.*, 2018). Rice, maize, and wheat are the major crops grown in the basin. As the basin has three major topographic regions (mountain, hill, and Terai) that include several districts, crop yield may be subjected to varying effects of change in climatic factors. Thus, a slight change in climatic factors may significantly affect the crop yields and jeopardize the overall livelihoods of the basin people. Studies focusing mainly on the variability of crop production over time because of climate change are scarce in the KRB, Nepal (Wahid *et al.*, 2017; Hussain *et al.*, 2018). Thus, it is important to assess the responses of crop yields with varying climatic factors, time, and topographic regions. In the present study, we collected crop yield data for maize, rice, and wheat from 16 districts in the KRB Nepal and observed the yield trends over 30 years (1987–2016) and related the yields with climatic factors (temperature and precipitation). We also observed the trends for the use of improved seeds, irrigation access, and fertilizer use.

2. Materials and methods

2.1 Study area

The KRB (26°54'47" N to 25°24'43"N latitude and 87°09'25"E to 87°15'32"E longitude) is a trans-boundary river system of a total 87,311 km^2 covering five counties in China (33% of its total area), 27 districts in Nepal (45%), and 16 districts in India (22%) (Bharati *et al.*, 2019). In Nepal, the basin covers three distinct regions: mountains, hills, and Terai (from north to south). The Terai is at less than 300 meters above sea level (m asl); it covers the northern part of the Indo-Gangetic plain and goes to the south of the Siwalik hills. The hills are at 300–2000 m asl, north of Siwalik to the south of the high mountains; the mountainous region is above 2000 m asl, from the north of the high mountains to the south of the Himalayas (Norbu, 2004). The major seasons are pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November), and winter (December to February) (Shrestha *et al.*, 2000). The monsoon season is influenced by the easterly wind; it causes an enormous amount of precipitation (about 80% of the annual total precipitation) and supports the production of major summer crops such as rice and maize. The westerly wind causes the winter precipitation and the occasional precipitation in the pre-monsoon season (with hailstorms and thunderstorms). This wind contributes the remaining 20% of the total precipitation. Out of 27 districts, we purposefully selected 16 districts which are in different topographic zones (mountain, hill, and Terai) in the Koshi basin Fig. 1). We used the secondary data of the respective districts available for the period from 1987 to 2016 (Fig. 1, Appendix 1).

2.2 Agricultural data

Maize, rice, and wheat yield data at the district level were collected from the Ministry of Agriculture and Livestock Development, Government of Nepal from 1987 to 2016. The growing season for maize, rice, and wheat crops were noted down by visiting different places in the KRB Nepal, and from secondary literature (Paudyal *et al.*, 2001; Nayava *et al.*, 2009; Ghimire *et al.*, 2012). The data were categorized according to three regions: Terai, hill, and mountain.

2.3 Climate data

Precipitation and the temperature are widely used climate variables to study the effects on crop yield (Peng *et al.*, 2004). We collected minimum temperature (T_{min}), maximum temperature (T_{max}), and total precipitation for the districts of the study area. Altogether 23 meteorological stations with complete climate data from 16 districts were considered ensuring that we had the required 30 years data needed to observe the climate impact as suggested by the World Meteorological Organization (IPCC-TGICA, 2007). Station-wise monthly climate data for each year were collected from the Department of Hydrology and Meteorology (DHM), Government of Nepal (Marahatta *et al.*, 2009; DHM, 2015, 2017). We collected the monthly climate data from June to November for rice, March to August for maize and from November (previous year) to May (next year) for wheat of mountain, hills, and Terai regions (Shrestha *et al.*, 2000; Maharjan and Joshi, 2013). The detail data for each station are shown in Appendix 1.

2.4 Non-climatic data

Four types of non-climatic data were collected from the Ministry of Agriculture and Livestock Development, Government of Nepal available for the different period. They were (i) sales of improved seeds of rice, wheat, and maize (1994–2017) (ii) chemical fertilizer consumption in Nepal (1992–2016), (iii) chemical fertilizers sale under subsidy program (2009–2016), and (iv) total irrigated land in Nepal (2004–2017).

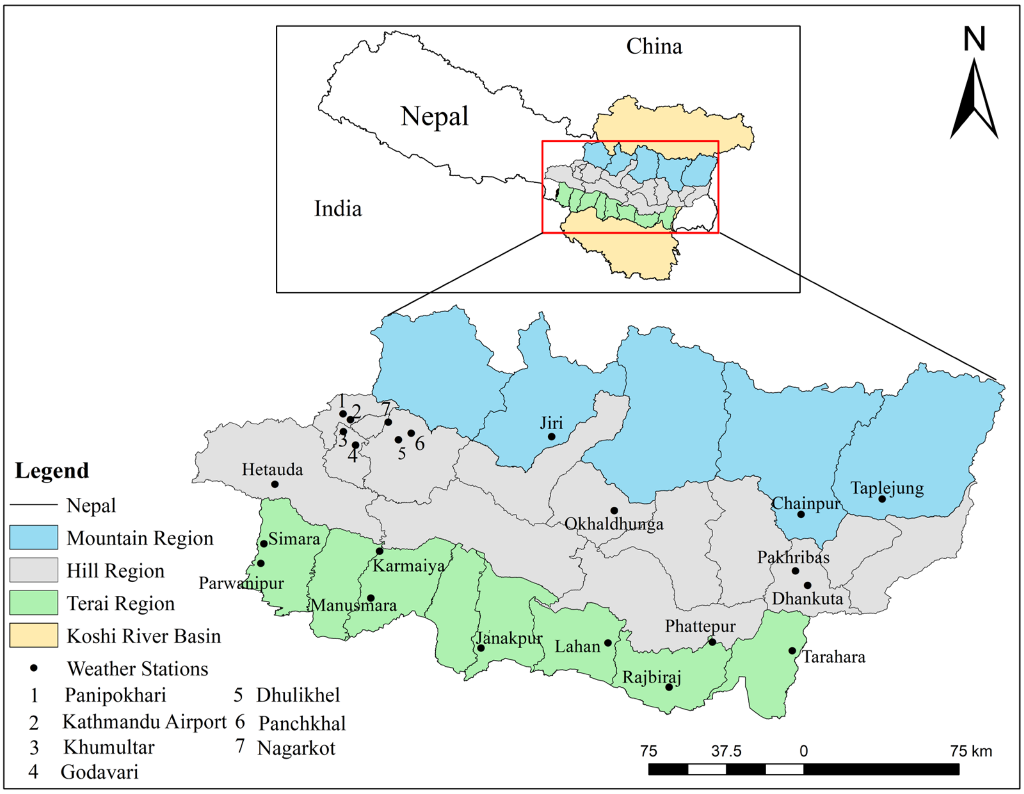

Fig. 1. Map of the study area showing districts and meteorological stations.

These data were only available at the country level at different time scales. Besides these non-climatic factors, we also observed the global carbon-dioxide (CO_2) concentration impact on crop yield. Because of the lack of availability of disaggregated data at the national and regional levels, we used global data as a proxy (Dlugokencky and Tans, 2019). The data was accessed from the two webpages (www.esrl.noaa.gov/gmd/ccgg/trends/ and https://datahub.io/core/co2-ppm#readme).

2.5 Data analysis

2.5.1 Relationship between crop yield, region, year, and climatic factors

To observe the relationship between climatic factors and crop yield, we used the seasonal average temperature (T_{avg} in ℃) and diurnal temperature range (DTR in ℃). The T_{avg} is derived as the average of minimum and maximum temperatures, and DTR is derived as the difference between the maximum and minimum temperatures for a day.

First, we used Spearman rank correlation in R 4.0.0 (R Core Team, 2020) to determine the relationships among different environmental variables (minimum temperature, maximum temperature, T_{avg}, DTR, precipitation). As there were high correlations ($R^2 > 0.94$) between T_{min}, T_{max}, and T_{avg}, we excluded T_{min} and T_{max} and only used T_{avg}.

We tested the effect of different region, year, DTR, T_{avg}, precipitation, and their interactions (year × region, year × DTR, year × T_{avg}, and year × precipitation) on the yield of maize, rice, and wheat maize by using the generalized linear mixed effect model (GLMM). In the model, we considered the yield as a dependent variable and region, year, precipitation, T_{avg}, DTR, and interactions (year × region, year × DTR, year × T_{avg}, and year × precipitation) as independent variables. The interactions of region × precipitation, region × T_{avg}, and region × DTR in most of the cases were insignificant. Thus, we did not consider the interactions of region and climatic factors in our analysis. However, region, as a separate variable, was kept as co-variate in the model. In the tests, we used districts as a random variable. Tests were carried out by using the lme4 package implemented in R 4.0.0 (R Core Team, 2020). In the tests, as data were right-skewed, we used gamma distribution with log link functions. To calculate the p-value, we used the drop1 function implemented in R and then again used the Chi-square test (R Core Team, 2020). All the figures were drawn by using Origin (Pro), version 2019b (Origin Lab Corporation, Northampton, MA, USA).

2.5.2 Trends of non-climatic data

The trends of different sales of improved seeds of maize, rice, and wheat yield (1994–2017), chemical fertilizer consumption in Nepal (1992–2016), chemical fertilizers sale under subsidy program (2009–2016), and total irrigated land in Nepal (2004–2017) were estimated by using the non-parametric Mann-Kendall (MK) test and Sen slope method (Mann, 1945; Kendall, 1975). The results obtained from the MK test and Sen slope was used to reflect the relationship between maize, rice, and wheat yield.

3. Results

3.1 Crop plantation seasons and yield

Maize is sown during March and harvested in August. Rice is transplanted during June and harvested in November. After the rice is harvested; wheat is sown in November and is harvested in

May. Thus, wheat is a winter (December–February) crop, maize is a pre-monsoon (March–May) crop, and rice is a monsoon (June–September) crop in the Koshi River Basin, Nepal.

The total average annual yield of maize was 2262 ± 656.9 kg/ha, rice was 2938 ± 1163.4 kg/ha, and wheat was 1927 ± 560.3 kg/ha. The maximum amount harvested for maize was 6400 kg/ha in 2014, and the minimum amount harvested was 900 kg/ha in 2002. The maximum amount harvested for rice was 6600 kg/ha in 1991, and the minimum amount harvested was 1170 kg/ha in 1999. The maximum amount harvested for wheat was 3670 kg/ha in 2013, and the minimum amount harvested was 899 kg/ha in 1988.

3.2 Relationship between crop yield, region, and climatic factors

Yield of all crops (maize, rice, and wheat) did not vary according to the regions (Terai, hill, and mountain) but significantly increased from 1987 to 2016 (Fig. 2, Table 1, Appendix 2). Maize yield slightly increased with increasing average temperature (Fig. 3a, Table 1). There was a significant effect of interactions of year × DTR and year × precipitation on maize yield (Table 1). Rice yields significantly decreased with increasing precipitation (Fig. 3b, Table 1) and average temperature (Fig. 3c, Table 1). There was a significant effect of interactions of year × region, year × DTR, and year × precipitation on rice yield (Table 1). Wheat yields slightly increased with increasing value of the DTR (Fig. 3d, Table 1). There was a significant effect of interactions of year × region, year × DTR, year × T_{avg}, and year × precipitation on wheat yield (Table 1).

3.3 Trends of non-climatic factors

The details of the trend of non-climatic factors in Nepal are given in Table 2. Results showed that from 1994 to 2017, the sale of improved rice and wheat seeds had a significant increasing trend of 110.47 metric tons (MT) and 114.43 MT per year respectively in Nepal. The consumption trend of fertilizer increased after 2009 when the government started a subsidy program in fertilizers. After the subsidy program, the fertilizer sale had a significant increasing trend of 42,828 MT per year. Similarly, the area of irrigated land also significantly increased from 2004 to 2016 by 37445 ha per year.

4. Discussion

Increasing crop yield is important for food security in a growing population in the world (Kang *et al.*, 2009). However, different climatic factors negatively and/or positively affect production, and thus it is important to observe their effects on sustainable agriculture production (Siwar *et al.*, 2009). The present study has shown that there was a variation in the yield of three major crops (maize, rice, and wheat) over the 30-year period, and has analyzed how different climatic factors affect these three major crop yields.

Cultivation of different crops in particular months was carried out according to the adaptability of crop type. Maize and wheat require less water and temperature, so they were cultivated during pre-monsoon and winter. Rice requires abundant water supply and high temperature, and is intensively cultivated during the warm growing seasons. This shows that different regions in

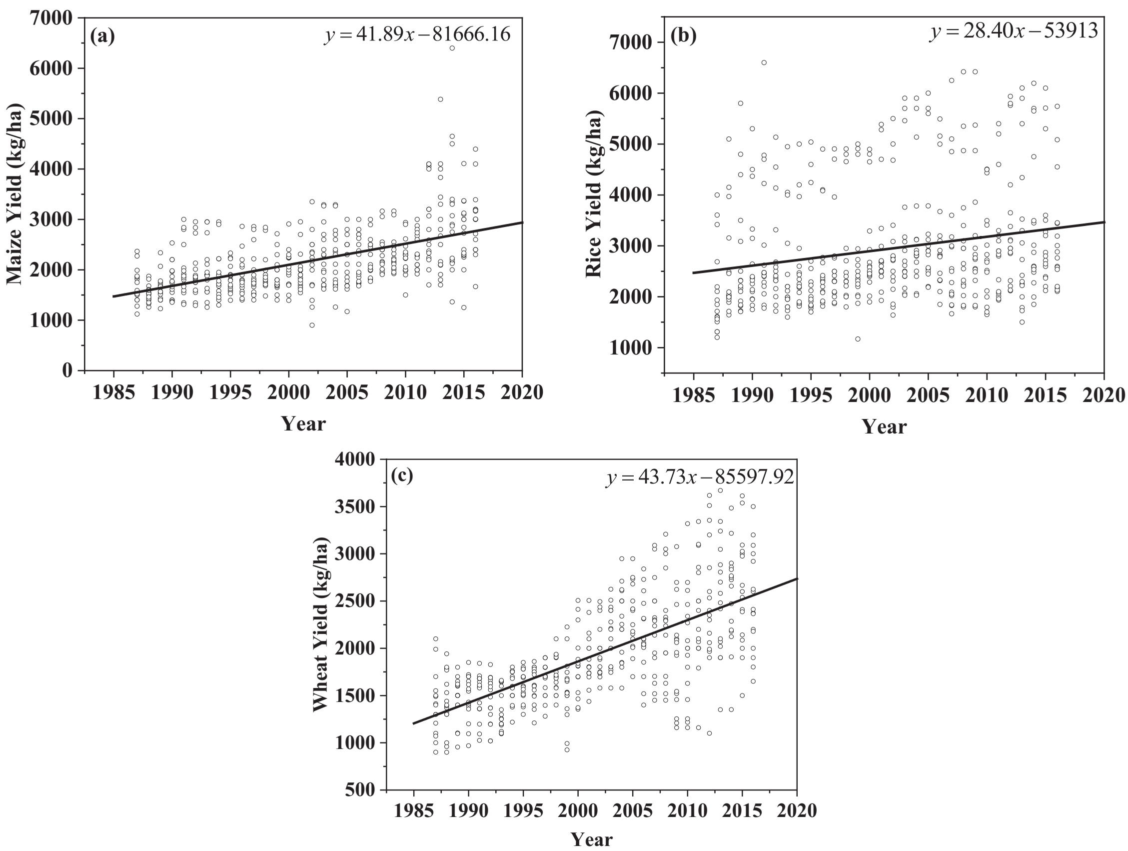

Fig. 2. Relationships between (a) maize yield and year, (b) rice yield and year and (c) wheat yield and year in the Koshi River Basin, Nepal.

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Table 1. Summarized results of the generalized linear mixed effect model (GLMM) testing the effects of region, year, DTR, T_{avg} and precipitation on the yield of rice, wheat and maize in Koshi River Basin, Nepal from 1987 to 2016. The p-values marked in bold are significant.

		Maize		Rice		Wheat	
Factors	**df**	**p-value**	**R^2**	**p-value**	**R^2**	**p-value**	**R^2**
Region	**2**	0.394	-	0.050	-	0.157	-
Year	29	**< 0.001**	0.784	**< 0.001**	0.647	**< 0.001**	0.862
Diurnal temperature range (DTR)	1	1.000	-	0.755	-	**0.028**	0.003
Average temperature (T_{avg})	1	**0.046**	0.005	**< 0.001**	0.042	0.423	-
Total precipitation	1	0.580	-	**0.011**	0.006	0.545	-
Year × region	58	0.260	-	**< 0.001**	0.125	**< 0.001**	0.058
Year × DTR	29	**< 0.001**	0.049	**0.004**	0.039	**< 0.001**	0.020
Year × T_{avg}	29	0.644	-	0.170	-	**< 0.001**	0.022
Year × precipitation	29	**0.003**	0.046	**0.009**	0.041	**0.039**	0.014

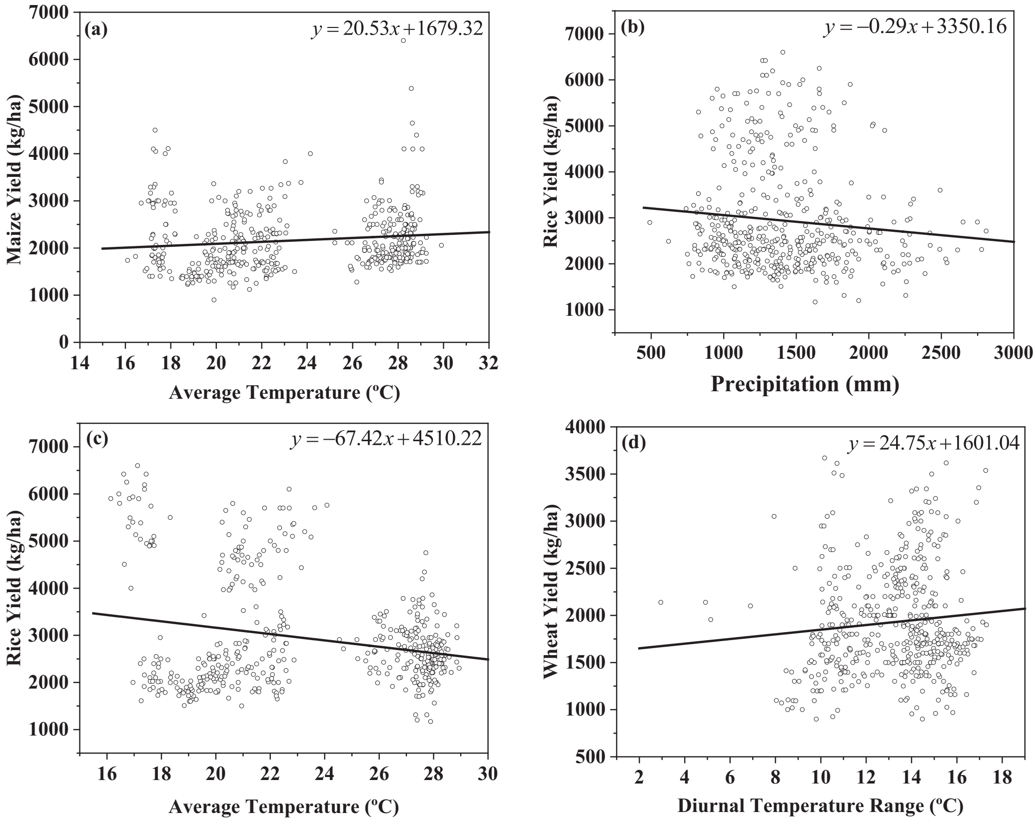

Fig. 3. Relationships between (a) maize yield and average temperature, (b) rice yield and precipitation, (c) rice yield and precipitation and (d) wheat yield and diurnal temperature range.

Table 2. The trend of the non-climate variables affecting crop yield over different periods in Nepal. The p-values marked in bold are significant.

Non-Climatic factors	**Statistics**	
	p-value	**Slope**
Improved rice seeds	**< 0.001**	110.47[a]
Improved wheat seeds	**< 0.001**	114.43[a]
Improved maize seeds	0.939	− 0.1823[a]
Chemical Fertilizers consumption	0.309	0.78[b]
Chemical fertilizer sale after subsidy program	**< 0.001**	42828[a]
Total irrigated land	**< 0.001**	37445[c]

a = MT per year; b = kg per ha per year; c = ha per year the world have their own unique crop production cycles, which require certain farming techniques to achieve optimum yield (Paudyal *et al*., 2001; Nayava *et al*., 2009; Ghimire *et al*., 2012). The quantity of different crop yield in the same place is not uniform and also varies over time or from year to year because of variations in environmental factors (Wahid *et al*., 2017; Hussain *et al*., 2018), soil conditions and use of fertilizers (Neenu *et al*., 2013), types of seed used (Pandey and Velasco, 2002; Karki *et al*., 2010; Chhetri *et al*., 2012; Paudel, 2012; DADO, 2016a) and also occurrence of natural calamities.

Yield of all crops did not vary according to the regions in our study. This is obvious as the region lies in the east Nepal and receives relatively more precipitation that is enough as required by different crops compared to the center and the west Nepal (Marahatta *et al*., 2009; DHM, 2015, 2017). However, the results showed a significant effect for the interaction between year and regions for rice and wheat, suggesting that the yields of these two crops were different among regions depending on the year.

Our finding of an increase in yield of maize, rice, and wheat from 1987 to 2016 is consistent with other studies from Nepal (Pant, 2012; Shrestha *et al*., 2012; Maharjan and Joshi, 2013; Aryal *et al*., 2016; Dhakal *et al*., 2016; Poudel and Shaw, 2016). The increase in yield is might be due to the use of improved agricultural techniques (DADO, 2016a, 2016b), better seeds (CDD and ASoN, 2017), improved cultivars (Pandey and Velasco, 2002; Karki *et al*., 2010; Chhetri *et al*., 2012; Paudel, 2012; DADO, 2016a), use of irrigation (Bahadur *et al*., 2015; Dahal *et al*., 2015; DADO, 2016b; Paudel, 2016), and use of fertilizers (Bhatta and Neupane, 2010; Shrestha, 2010; Neupane, 2011; Neenu *et al*., 2013; Henderson *et al*., 2016). There is also use of improved crop varieties, input levels, timing of cropping, and managing water sources for better yield elsewhere in the world, including Nepal (Neupane, 2011; Lobell and Gourdji, 2012; Chen *et al*., 2015; Ara *et al*., 2017).

The finding of a slight increase in maize yield with increasing temperature in our results is consistent with other studies (Chen *et al*., 2015; Liu *et al*., 2017) but different to Zhang and Huang (2012) who mentioned that the warmer temperature and less precipitation during the maize growing season have a negative impact the yield. High temperature has positive effects on the seedling growth and the maturity phases of maize crop resulting into a better maize yield (Yin *et al*., 2016).

In our study, rice yield significantly decreased with increasing temperature and precipitation showing that increased temperature might affect the physiological development of rice inhibiting yield. Increasing temperatures reduce the soil moisture, creating water stress on rice (Fukai and Cooper, 1995). A study by Boote *et al.* (2005) on rice revealed that the yield decreases by 10% above the T_{avg} of 25℃ up to 36℃ after which the plant cannot form the grain. Similarly, in a changing climate, Tashiro and Wardlaw (1989) revealed the decline of the grain mass by 4.4% in 1℃ increase in temperature above 25℃ and Baker and Allen (1993) mentioned the possibility of yield loss by 9.6 to 10% in every 1℃ increase in temperature above 25℃. Ara *et al.* (2017) showed the negative impact of temperature in the yield of two rice varieties (*Aus* and *Aman*) in Bangladesh. Likewise, Oerke (2006) also mentioned that the high temperatures and high precipitation often result in the growth of pests and diseases, especially in the tropical and sub-tropical areas that might affect the yield of various crops. Chakraborty *et al.* (2000) discussed the rice blast disease that can affect the rice growth and yield because of increasing temperature, especially in the Asian rice-growing region. High amount of rain also causes flooding, landslides and wash the top soils leading to degradation of land and thus result in a decrease of crop yield including rice (Mohammadi *et al*., 2020).

Wheat yields slightly increased with increasing value of the DTR. This finding resembles with other studies in Nepal showing the increment in the DTR is because of a higher rate of increasing maximum temperature than the minimum (Marahatta *et al*., 2009; DHM, 2015; DHM, 2017). DTR increment results from increase maximum temperature that shows overall positive correlation of wheat yield in north China (Zhang *et al*., 2013). We have considered November to May as a wheat-growing season, which includes winter and pre-monsoon season in Nepal. Winter includes the seedling, tillering, and plant elongation stage and later season includes the spike formation, flowering, ripening and harvesting stage (DADO, 2016a). During the later stage, the temperature is comparatively higher than the earlier stage and hence the yield gets benefited, especially when the grain formation or crop development rates are more sensitive to minimum temperature than the maximum (Wilkens and Singh, 2003; Tao *et al*., 2008). The increased DTR during the growing season also shows the warming days and cooling night, which is beneficial for crop growth as the photosynthetic rate increase during the day and respiration rate reduce during the night (Leopold and Kriedemann, 1975; Ryan, 1991; Chen *et al*., 2015). A study by Chakrabarti *et al.* (2011) in India found that the low temperatures during the reproductive stage of wheat cause yield reduction because of pollen sterility. Their study showed an increasing temperature enhanced the pollen germination it results into a high wheat yield.

There was a significant effect of interactions of year × DTR on maize, rice and wheat yields, meaning that the DTR is variable in different years and the yield partly depends on the variation of the DTR. Thus, DTR is probably the most important factor in the life cycle of maize, rice, and wheat. Similarly, the significant effect of interactions of year × regions for rice and wheat yield might be due to use of different farming techniques, use of a different rotation of crops, change in cultivation patterns or even because of variations in the occurrence of natural calamities in different regions (Neupane, 2011; Lobell and Gourdji, 2012; Chen *et al*., 2015; Ara *et al*., 2017). There were also variations in precipitation and temperature during different years (Agrawala *et al*., 2003) and the yield of rice and wheat depend on favorable precipitation or temperature in a year thus there was a significant effect of interactions of year × precipitation on rice yield and also a significant effect of interactions of year × precipitation and year × T_{avg} on wheat yield.

The variation in crop yield of maize, rice, and wheat is also partly because of their existing plant physiology. Considering the plant physiology of selected crops in the study area, rice and wheat are C3 plants and maize is a C4 plant. During photosynthesis, C3 plants initially convert carbon dioxide into

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3-carbon compounds and C4 plants convert it into four-carbon compounds (Ehleringer and Cerling, 2002). Thus, the C3 and C4 plants respond differently to the changing temperature during photosynthesis and vary the amounts of carbon dioxide in the atmosphere and water availability. C4 plants are more productive photosynthetically compared with C3 plants and can cope with higher temperatures and low water availability (Ehleringer and Cerling, 2002). Besides this, crop yield is also partly depended on its existing genetic conditions and therefore, maize, rice, and wheat differ in their genetic conditions resulting in their yields (Lobell and Gourdji, 2012).

Amthor (1998) discussed that, in the past 100 years, crop yield in most of the countries increase along with the increased in atmospheric carbon dioxide. From 1987 to 2016, the atmospheric CO_2 concentrations measured at Mauna Loa in Hawaii, the United States of America increased by 55 ppm (Dlugokencky and Tans, 2019). A study by Ainsworth *et al*. (2008) on the effects of CO_2 concentration in C3 crops (rice, soybean and wheat) showed about 0.065% yield increase per ppm. Based on this; Lobell *et al*. (2011) explained about a 3% increase in rice and wheat yield from 1980 to 2008, when the CO_2 concentration increased by 47 ppm. Thus, in our study from 1987 to 2016, the increased CO_2 concentration of 55 ppm would have contributed about 3.5% to the increase in the C3 crop yield (rice and wheat). For the maize, as discussed earlier, it has a C4 photosynthetic pathway which, unlike C3 plants, has no stimulation of photosynthesis to the increased CO_2 concentration (Malla, 2008; Leakey, 2009).

5. Conclusions

Our study assessed the maize, rice, and wheat crop yield trends over 30 years (1987–2016) in the Koshi River Basin, Nepal. It was found that rice was produced in the highest amount, followed by wheat and maize. All crop types yield steadily increased in the recent years. There was a negative impact of increasing temperature and precipitation for rice, but a positive impact of increasing DTR for wheat. The effects of interactions of year and factors such as DTR, precipitation and T_{avg} on different crops were variable. It is concluded that crop production is variable over the study period (1987–2016) and are affected by different climatic factors. It is necessary to observe how crop production is affected to ensure food security for increasing human population. Although this study covers only three crop types in the Koshi River Basin in Nepal, it is expected to serve as a model for further studies.

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Appendix 1. Details of selected districts and meteorological stations in the Koshi River Basin, Nepal.

District	Station Name	Latitude (ºN)	Longitude (ºE)	Elevation (m)	Station Index
Dolakha[a]	Jiri	27.63	86.23	1877	1103
Sankhuwasabha[a]	Chainpur	27.29	87.31	1277	1303
Taplejung[a]	Taplejung	27.35	87.67	1744	1405
Kathmandu[b]	Panipokhari	27.72	85.32	1329	1039
	Kathmandu Airport	27.70	85.35	1337	1030
Lalitpur[b]	Khumaltar	27.65	85.32	1334	1029
	Godavari	27.59	85.37	1527	1022
Makwanpur[b]	Hetauda	27.42	85.02	452	906
Bhaktapur[b]	Nagarkot	27.69	85.52	2147	1043
Kavre[b]	Dhulikhel	27.61	85.56	1543	1024
	Panchkhal	27.64	85.62	857	1036
Okhaldhunga[b]	Okhaldhunga	27.30	86.50	1731	1206
Dhankuta[b]	Pakhribas	27.04	87.29	1720	1304
	Dhankuta	26.98	87.34	1192	1307
Bara[c]	Simara	27.16	84.98	137	909
	Parwanipur	27.06	84.96	87	911
Sarlahi[c]	Karmaiya	27.13	85.48	139	1121
	Manusmara	26.92	85.44	90	1118
Dhanusa[c]	Janakpur	26.71	85.92	76	1111
Siraha[c]	Lahan	26.73	86.47	110	1215
Saptari[c]	Rajbiraj	26.54	86.74	68	1223
	Phattepur	26.73	86.93	83	1212
Sunsari[c]	Tarahara	26.69	87.27	120	1320

[a] (mountain districts), [b] (hill districts), [c] (Terai districts)

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Appendix 2. The detailed results of the generalized linear mixed model effect model (GLMM) testing the effects of region, year, DTR, T_{avg} and precipitation on maize, rice and wheat yield in Koshi River Basin, Nepal over the period 1987–2016. The p-values marked in bold are significant.

			Maize			
Factors	**df**	**Sum Sq**	**Mean Sq**	**F value**	**p-value**	**R^2**
Region	2	0.46	0.23	13.82	0.394	-
Year	29	14.12	0.49	29.38	< **0.001**	0.784
Diurnal temperature range (DTR)	1	0.00	0.00	0.01	1.000	-
Average temperature (T_{avg})	1	0.08	0.08	5.03	**0.046**	0.005
Total precipitation	1	0.01	0.01	0.80	0.580	-
Year × region	58	1.17	0.02	1.22	0.260	-
Year × DTR	29	0.88	0.03	1.84	< **0.001**	0.049
Year × T_{avg}	29	0.44	0.02	0.92	0.644	-
Year × precipitation	29	0.84	0.03	1.74	**0.003**	0.046
			Rice			
	df	**Sum Sq**	**Mean Sq**	**F value**	**p-value**	**R^2**
Region	2	0.61	0.30	38.09	0.050	-
Year	29	5.77	0.20	24.92	< **0.001**	0.647
Diurnal temperature range (DTR)	1	0.00	0.00	0.22	0.755	-
Average temperature (T_{avg})	1	0.37	0.37	46.62	< **0.001**	0.042
Total precipitation	1	0.06	0.06	7.18	**0.011**	0.006
Year × region	58	1.11	0.02	2.40	< **0.001**	0.125
Year × DTR	29	0.35	0.01	1.50	**0.004**	0.039
Year × T_{avg}	29	0.28	0.01	1.22	0.170	-
Year × precipitation	29	0.37	0.01	1.60	**0.009**	0.041
			Wheat			
	df	**Sum Sq**	**Mean Sq**	**F value**	**p-value**	**R^2**
Region	2	0.461	0.230	28.528	0.157	-
Year	29	20.165	0.695	86.113	**< 0.001**	0.862
Diurnal temperature range (DTR)	1	0.073	0.073	9.076	**0.028**	0.003
Average temperature (T_{avg})	1	0.014	0.014	1.768	0.423	-
Total precipitation	1	0.005	0.005	0.621	0.545	-
Year × region	58	1.359	0.023	2.902	**< 0.001**	0.058
Year × DTR	29	0.458	0.016	1.958	**< 0.001**	0.020
Year × T_{avg}	29	0.522	0.018	2.229	**< 0.001**	0.022
Year × precipitation	29	0.326	0.011	1.391	**0.039**	0.014