Assessment of drought impacts on crop yields across Nepal during 1987–2017

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Abstract
Drought influences agriculture, hydrology, ecology and socio-economic systems globally. As agriculture is the primary source for livelihoods and contributes to ~27% of Nepal’s total gross domestic product, it is essential to understand the impact of drought on maize and wheat crop yields to minimize the drought-related risks. This study presents insights about agricultural drought across Nepal during 1987–2017 using the Standardized Precipitation Evapotranspiration Index (SPEI). The temporal evolution of SPEI time series has revealed frequent occurrences of drought episodes during the cropping cycle of summer maize and winter wheat crops. Moreover, the turning point of the drought was detected in 2000 (1987–2000, 2001–2017) in different regions. The averaged frequency for the SPEIs (1, 3, 6 and 12) of drought years for summer maize (winter wheat) in the western, central and eastern regions increased by 13% (12.5%), 6% (7.5%) and 7% (8%), respectively, from 1987–2000 to 2001–2017. The relationship between Standardized Yield Residual Series, the detrended SPEI at 1–12 lags and soil moisture was observed for both crops. The most correlated crop growth period for summer maize and winter wheat was the sowing and growing period, respectively, indicating the sensitive period of water deficit. Besides, the correlation performed in the two sub-periods (1987–2000 and 2001–2017) shows that drought impacts increased in the western and central regions, whereas they substantially decreased in the eastern region during the cropping period of summer maize. However, the drought sensitivity for winter wheat was decreased in the western region but significantly increased in the central and eastern regions of Nepal. The results of this study provide important information useful for policymakers in monitoring and mitigating the drought-related risks on maize and wheat crops in Nepal.

KEYWORDS
agriculture, drought, Nepal, precipitation, SPEI, SYRS
INTRODUCTION

Drought affects many aspects of society and the environment globally with widespread consequences (Haile et al., 2020c). It is an unpredictable natural phenomenon (Mukherjee et al., 2018) that is aggravated by the changing climate and anthropogenic drivers (Mishra and Singh, 2010; Sheffield et al., 2012). Ongoing climate change has accelerated and increased extreme weather events, such as drought and floods (IPCC, 2012; Leng et al., 2015; Haile et al., 2020b), with substantial regional variations. Among different categories of drought, an agricultural drought is a complex and poorly understood hazard (Mishra and Singh, 2010; Dai, 2011). It creates a harsh environment in which the soil moisture becomes insufficient for plant growth, causing crop yield failure and food insecurity (Fahad et al., 2017; Mao et al., 2017; Haile et al., 2020a). The impacts of agricultural drought are notably higher in rain-fed agricultural countries, including Nepal (Miyan, 2015; Chen et al., 2016; Potopová et al., 2016). Thus, region-specific explorations of agricultural drought are critical for effective and efficient drought monitoring and adaptation strategies.

Several previous studies have examined the influence of climate change on crop yields over Nepal (Poudel and Kotani, 2012; Bhatt et al., 2014; Thapa-Parajuli and Devkota, 2016; Pratiksha et al., 2017) and have reported the inconsistent relationship between crop yield and climatic variability. Rise in temperature and change in precipitation patterns have been observed to affect the cropping cycle and crop production adversely (Maharjan and Joshi, 2013). The wheat production in Nepal has a positive response to precipitation; however, an increase in temperature controls the production level (Thapa-Parajuli and Devkota, 2016). Regionally, the maize production in central Nepal is negatively influenced by climatic variation during summer, while the impact is insignificant on wheat production (Pratiksha et al., 2017). In eastern Nepal, warming has negative impacts on the yield of maize and wheat (Bhatt et al., 2014). Similarly, climate change has exacerbated issues in the farming system, such as drought stress, crop diseases and low yield in different regions of Nepal (Manandhar et al., 2011; Dhakal et al., 2016). Recently, Khatiwada and Pandey (2019) reported a noticeable influence of precipitation on crop yield variability in different districts of western Nepal. However, none of the studies mentioned above has analysed the impact of drought on crop yield over Nepal.

In Nepal, the agricultural system is highly dependent on monsoonal rainfall (Gentle and Maraseni, 2012). Moreover, agriculture contributes to around 27% of Nepal’s gross domestic product (GDP), being a very crucial sector in the overall economy of Nepal. However, agriculture in Nepal is suffering from lots of natural hazards, including droughts, floods, soil erosion and landslides (Dhakal, 2015). More importantly, droughts have occurred frequently over the past decades in Nepal, where climate change played a crucial role in aggravating the drought conditions (Wang et al., 2013). For instance, the summer drought in 2015 severely impacted crop yield, affecting more than 80% of the population in the western region (Gyawali, 2016). Thus, there is a pressing need to evaluate agricultural droughts quantitatively in the context of climate change. However, there are few studies conducted in Nepal mainly focusing on the spatio-temporal drought variations revealing increased drought characteristics (i.e. frequency, intensity and duration) (Sigdel and Ikeda, 2010; Wang et al., 2013; Dahal et al., 2015; Kafle, 2015). Nevertheless, those studies did not address drought impacts on crop yields in the context of climate change. Therefore, it is crucial to quantify the drought risk on crop yields over Nepal with a drought index that considers temperature as one of the main input parameters for calculating potential evapotranspiration (PET). This will be beneficial to mitigate the effects of drought and adopt a healthy farming system to maximize agricultural production.

Different drought indices have been developed and defined with different climatic variables, such as precipitation, temperature and soil moisture (Mishra and Singh, 2010; Zargar et al., 2011; Potopová et al., 2016). Among them, the Palmer Drought Severity Index (PDSI) (Palmer, 1965), the Standardized Precipitation Index (SPI) (McKee et al., 1993) and the Standardized Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) are the most used drought indices.

The SPI only uses the precipitation variable for the calculation of drought at different timescales, while making it possible to choose a timescale for meteorological, agricultural and hydrological applications (McKee et al., 1993; Manatsa et al., 2010). In contrast, the PDSI considers water balance to calculate drought on a fixed timescale, limiting its applicability to analysing meteorological and agricultural drought (Palmer, 1965; Zhao et al., 2017). The SPEI overcomes the limitations of the SPI and PDSI and considers both precipitation and temperature variables for calculating drought at different timescales (Vicente-Serrano et al., 2010; Yao et al., 2018). The SPEI is typically developed for drought assessments in the context of global warming (Vicente-Serrano et al., 2010), where the role of temperature is quantified through the PET. Different studies have used the SPEI to analyse drought worldwide; for instance increased drought severity and frequency were detected by the SPEI in most of Pakistan due to the rise in temperature (Ahmed et al., 2018). Similarly, several studies have used the SPEI to quantify the impacts of drought on crops...
globally (Potop et al., 2012; 2014; Dutta et al., 2015; Ribeiro et al., 2019; Tian et al., 2020). Thus, the SPEI was selected to quantify drought conditions at 1–12 month lags, which is useful to evaluate the impacts of drought on crop yields over different regions of Nepal.

The current study aims to analyse the impact of drought on two major cereal crops, maize in summer (hereafter summer maize) and wheat in winter (hereafter winter wheat), over three different regions of Nepal (western, central and eastern) during 1987–2017. Specifically, this study has three objectives: (a) to present the spatial–temporal representation of drought evolution and the frequency over different regions, (b) to evaluate the influence of drought on the crop yield of summer maize and winter wheat and (c) to study the changes of the relationship between the drought and crop yield during two periods (1987–2000 and 2001–2017). The study is directed to fill the gaps in the lack of systematic studies on agriculture drought and its impacts on the agrarian society of Nepal.

2 MATERIALS AND METHODS

2.1 Study area

Nepal is a landlocked country located between 80° 04' to 88° 12' E latitude and 26° 12' to 30° 27' W longitude with an area of 147,516 km². A wide altitudinal range from ~60 m above sea level to 8,848 m above sea level (at Mount Everest) in the country (Figure 1) gives rise to diversified topography and climate. The South Asian monsoon governs the climatology of the country with high spatial and seasonal variability of precipitation distribution (Sharma et al., 2020b). The summer monsoon (June–September) contributes ~80%, while pre-monsoon (May–March), post-monsoon (October–November) and the westerly in winter (December–February) contribute 13%, 4% and 3% of the annual precipitation, respectively (Sharma et al., 2020c). Regionally, central and eastern Nepal receives more monsoonal precipitation in summer, while the western region receives the highest westerly precipitation in winter (Sharma et al., 2020a). Moreover, the distribution of precipitation is determined by local scale parameters, such as orography, wind exposure and direction of the mountain range (Hamal et al., 2020b). During the La Niña years, the moisture divergence with strong northwesterly wind anomalies drives the dry winter years across Nepal (Hamal et al., 2020a).

The air temperature of the country is high in the lowlands and gradually decreases towards high altitude in the north (DHM, 2017). According to a new climatic classification, five climate belts occur in Nepal with tropical savannah in the southern lowlands, temperate in the hilly regions and polar tundra frost climate in the

![FIGURE 1](#) The location of the study area, Nepal, is shown. Nepal is divided into western, central and eastern regions in the present study, showing the districts (hatched) and climatological stations (triangle) used in the study.
Himalaya (Karki et al., 2017). The air temperature in summer is highest followed by the pre-monsoon, post-monsoon and winter season, respectively (DHM, 2017). The highest (lowest) temperature is observed in southern lowland (high mountains) during May and June (December and January). Moreover, the highest rate of warming (~0.05°C-year⁻¹) was observed in the pre-monsoon, while it was in the range ~0.025–0.036°C-year⁻¹ for other seasons during 1980–2016 (Karki et al., 2017).

Although the agricultural land has increased from 151.2 × 10² km² to 438.8 × 10² km² between 1990 and 2010 (Paudel et al., 2018), the climatic variables (precipitation and temperature) are key factors that control agricultural productivity and thus govern social and economic development. The frequent occurrences of drought bring crop losses and subsequently food insecurity (Friel et al., 2014; Gyawali, 2016). The major cereal crops are rice, maize, millet, wheat, barley and buckwheat. Nepalese farmers are practising diversified farming systems and adapting potential measures to hedge against erratic and uncertain weather conditions (Rohwerder, 2016). The annual production of crop yield in Nepal differs over the three different regions. Thus, we studied the impacts of drought on crop yields over three distinctive regions (western, central and eastern) of Nepal, as in Figure 1.

2.2 | Data

A total of 50 meteorological stations were selected and screened for the study, maintained by the Department of Hydrology and Meteorology of Nepal. These stations featured both temperature (maximum and minimum) and precipitation data during the study period (1987–2017). Quality control was conducted to discard those stations having more than 5% missing data. Additionally, a homogeneity test was performed to test the fluctuations in data series using the RHtest software package (R Core Team, 2013). After quality control, stations which featured continuous temperature and precipitation data were used for analysis. Thus, 38 stations were found suitable with 16, 10 and 12 stations in the western, central and eastern regions of Nepal, respectively (Figure 1).

Besides, data for two primary cereal crop yields (summer maize and winter wheat) were collected from 40 districts of Nepal (Figure 1), which are mostly located with the rain gauge stations. The crop yield data from 1987 to 2017 were collected from a yearly report published as statistical information on Nepalese agriculture (MoAD, 2017). The agriculture district profile was taken as a reference to fill the missing year values, which is jointly developed by the Ministry of Agricultural Development (MoAD), Government of Nepal, and the International Centre for Integrated Mountain Development.

More information on the agriculture district profile can be found on the web-portal (http://geoapps.icimod.org/agricultureatlas/index.html, accessed in December 2019).

Soil moisture is an important parameter to quantify drought and its impacts on the crop yield. We use soil moisture with a spatial resolution of 0.25° × 0.25° provided by ERA5 spanning the period between 1987 and 2017. ERA5 is a recently released fifth-generation global atmospheric reanalysis project developed by the European Centre for Medium-Range Weather Forecasts, which provides improved data for atmospheric models and assimilation systems (C3S, 2017). Recently, Sharma et al. (2020d) validated the ERA5 precipitation product using an extensive gauge network (220) from Nepal during 1987–2015, revealing that ERA5 is a good alternative for precipitation monitoring in the country.

2.3 | Drought quantification

The widely used drought index SPEI was used to characterize drought over different regions of Nepal during the study period. The SPEI uses precipitation (\(P_i\)) and potential evapotranspiration (PET\(_i\)) in its drought calculation. \(P_i\) and PET\(_i\) were used to calculate the monthly water balance (\(D_i\)):

\[
D_i = P_i - \text{PET}_i
\]  

(1)

There are different methods for the calculation of PET\(_i\), varying from simple such as Thornthwaite (Thornthwaite, 1948) or Hargreaves (Hargreaves and Samani, 1985), to complicated ones such as the Penman–Monteith method (Allen et al., 1998). Although the Food and Agriculture Organization of the United Nations (FAO) has accepted Penman–Monteith as a standard method, in the present study PET\(_i\) was calculated through the Hargreaves method because of limitations of the data (Hargreaves and Samani, 1985). This method has already been applied over South Asia (covering Nepal) for drought analysis at a different timescale and is successful in monitoring drought in real-time (Aadhar and Mishra, 2017).

After calculating \(D_i\) at each station, the results were passed through the SPEI R package to calculate the SPEI at multiple timescales (http://cran.r-project.org/web/packages/SPEI). Then \(D_i\) was fitted using the log–log distribution function \(f(x)\) in Equation (2). The multiple time series of the SPEIs were obtained as SPEI1, SPEI3, SPEI6 and SPEI12 using Equation (3).
where \( \alpha, \beta \) and \( \gamma \) are the scale, shape and origin parameters, respectively.

\[
f(x) = \left[1 + \left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1}
\]

(2)

When \( P \leq 0.5 \), \( P = 1 - f(x) \); when \( P > 0.5 \), \( P = 1 - P \), and the sign of the SPEI is reversed. The constants are \( c_0 = 2.515517 \), \( c_1 = 0.802853 \), \( c_3 = 0.010328 \), \( d_1 = 1.432788 \), \( d_2 = 0.189269 \) and \( d_3 = 0.001308 \).

The SPEI time series give positive and negative values which represent the wet and dry conditions. The threshold value of \(-1\) (SPEI \( \leq -1 \)) was used to determine the drought condition (Tan et al., 2015). The different categories of drought are summarized in Table 1.

The regional SPEI was obtained by averaging SPEI values at each station over three different regions as these stations and regions show a similar seasonal climatology with large precipitation peaks during the summer season (June–September) (Sharma et al., 2020a; 2020b). This approach is adopted from Liu et al. (2018) when all stations located in the study area have the same climatic conditions. The SPEI calculated for various lags contained the memory of moisture conditions from the previous and the current month (Potop et al., 2014). Technically, the SPEI3 indicates the water condition of the current month and the past 2 months (e.g. for the SPEI3 in April, February–March–April), while the SPEI12 provides the memory of moisture from 11 months to date. SPEI1, SPEI3–SPEI6 and SPEI12 are used to represent meteorological, agricultural and hydrological drought, respectively (Li et al., 2015).

The calculated regional SPEI has the information of the SPEI of the whole annual calendar, that is, January to December. If we use such SPEI than it could bring uncertainties in the drought analysis for the winter wheat and summer maize as they have different months of cropping cycle and stages. Therefore, we reorganized the SPEIs for each crop based on the cropping cycle. The SPEIs at different timescales have information from February to September of the same year for summer maize and from October of the previous year to May of the current year for winter wheat. The response of the drought conditions to crop varies in all stages, and its effects can be seen in the rate of germination and emergence; development of root, leaf and stem, flowering, pollination, grain-filling as well as the quality of the grains (Prasad et al., 2008; Hussain et al., 2018). The whole phenological period is divided into three sub-periods, that is, sowing, growing and harvesting (Table 2). The reference for the cropping calendar of crops is obtained from the website of the FAO (http://www.fao.org/giews/countrybrief/country.jsp?code=NPL, accessed in December 2019).

### 2.4 Drought frequency estimation

Drought frequency was used to assess the drought that occurred during the study period (Tan et al., 2015). It is calculated as a fractional frequency and shows the probability of the months that have SPEI value less than or equal to the threshold level of drought (SPEI \( \leq -1 \)) (Table 1). It can be calculated as:

\[
\text{frequency} = \frac{n}{N}
\]

(4)

where \( n \) is the number of drought months and \( N \) is the total number of months for the study period.

### 2.5 Standardized residual yield series (SRYS) calculation

The crop yield data contain a yearly regional level of summer maize and winter wheat for the study period 1987–2017. Due to advances in the technology and adaptation practices in agriculture sectors, crop production is generally experiencing an increasing trend. The linear regression method was used for detrending to remove the technological/linear trend in the yield. The residual of yields represents the effects of the weather on the yield (Potopová et al., 2016; Liu et al., 2018). The SRYS was calculated using:

\[
\text{SRYS} = \frac{Y_i - \mu}{\sigma}
\]

(5)

| TABLE 1 | Drought classification based on Standardized Precipitation Evapotranspiration Index (SPEI) values |
|---------|---------------------------------------------------|
| SPEI value | Drought category |
| \(-1.5 \leq \text{SPEI} \leq -1\) | Moderate |
| \(-2 \leq \text{SPEI} \leq -1.5\) | Severe |
| \(\text{SPEI} \leq -2\) | Extreme |
where \( y_1 \) is the residual of the detrended yield, \( \mu \) is the mean of the residuals of the detrended yield and \( \sigma \) is the standard deviation. The various yield loss categories are defined in Table 3.

### 2.6 Modified Mann–Kendall trend analysis

The modified Mann–Kendall trend test was used to identify the existence of crop yield trend and the significance level of the crop yield. The test was calculated using the modifiedmk package in R software at a 95\% (\( p < .05 \)) significance level. The magnitude of the slope of the crop yield gives the temporal change in the yield.

### 2.7 Correlation analysis

The impact of the SPEIs and soil moisture on the yield of the summer maize and winter wheat was analysed using the non-parametric Spearman’s rho correlation coefficient with a significance threshold of \( p < .05 \) (95\%), respectively. The SPEI at different timescales and soil moisture trends are removed/detrended before calculating the correlation with the SYRS over the different regions. The quantitative characteristics in the correlation analysis are missed if the trend is adopted (Wu et al., 2007). The correlation was analysed between the SYRS, soil moisture and the SPEI for the entire period (1987–2017). Further, the correlation of the SPEIs was also carried out with the particular line segment, that is, 1987–2000 and 2001–2017, to understand crop variability associated with drought in the respective decades.

### 3 RESULTS

#### 3.1 Temporal evolution of drought

The temporal evolution of regional averaged SPEIs over different regions of Nepal for the cropping month of summer maize (February–September) reveals the frequent occurrence of drought episodes during 1987–2017, shown in Figure 2a,c,e. The 1–12 month lags of the SPEI show the alternating dry and wet conditions during the cropping season of summer maize, indicating the drought timing and persistence over the different regions. The western region has experienced consecutive drought episodes between 2002 and 2007 (Figure 2a). The central region has many wet episodes during 1995–2002 and dry episodes during 2007–2017 (Figure 2c). Meanwhile, the eastern region of the country also has continuous drought events between 2007 and 2017 (Figure 2e). The most severe drought years were 1992, 2006, 2009, 2012 and 2015 in all three regions. The result also shows that the western region has experienced many drought episodes followed by the eastern (8–21) and central (8–18) regions of Nepal.

The temporal evolution of the SPEIs at 1–12 month lags for the cropping month of winter wheat (October–May) has a similar pattern of dryness and wetness to summer maize between 1987 and 2017 (Figure 2b,d,f). A noticeable increase in drought episodes was observed for both summer maize and winter wheat across Nepal after 2000. When the time series data lack a significantly increasing or decreasing trend, then there exists a turning point (Chen et al., 2014; Haile et al., 2020b). The turning point was detected in 2000 with a non-statistically upward trend during 1987–2000 and a statistically significant downward trend during 2001–2017 (Figure S1). It should be noted that there was a rapid shift of severe wet episodes to dry episodes between 1987–2000 and 2001–2017 in three regions of Nepal (Figure 2). Moreover,

| SYRS value | Yield loss category |
|------------|---------------------|
| −1.0 ≤ SYRS ≤ −0.5 | Low yield loss |
| −1.5 ≤ SYRS ≤ −1 | Moderate yield loss |
| SYRS ≤ −1.5 | High yield loss |

Note: SYRS, Standardized Yield Residual Series.
the droughts are even getting aggravated during the period 2007–2017 in the central and eastern regions (Figure 2d,f).

3.2 | Frequency of drought

The temporal distribution of drought frequency for summer maize and winter wheat shows year-to-year variation across the country (Figure S2). The yearly drought frequency with dry months (SPEI ≤ −1) ranged between 8% and 67%. The frequency of dry months reached ≥50% in most of the severe drought years (e.g. 1992, 1994, 2006, 2009, 2012 and 2015). The averaged SPEI (1, 3, 6 and 12) drought frequency of summer maize (winter wheat) in the western, central and eastern regions during the study period was 0.25 (0.24), 0.20 (0.19) and 0.23 (0.21), respectively. The western region has slightly more dry years with dry months than the eastern and central regions (Figure S2). The frequency at different accumulation periods of the SPEIs suggested an increase of drought with timescale. The result shows that a 12 month drought year has a more extended frequency, that is, the number of dry months is higher, indicating that hydrological drought is more severe. The short-term and medium-term water deficit is reflected by the 1–3 month and

**FIGURE 2** The temporal time series of the Standardized Precipitation Evapotranspiration Index (SPEI) at 1–12 month lags at different regions (a), (b) western, (c), (d) central and (e), (f) eastern) for the cropping season of summer maize and winter wheat during 1987–2017. The red colour indicates drying, and the blue colour indicates wetting.
6 month SPEIs, respectively, whereas long-term drought is reflected by a more extended period of water deficit, that is, SPEI12 (Potop et al., 2014; Potopová et al., 2015).

The drought years have frequently occurred in the cropping period for summer maize and winter wheat during 1987–2017 (Figure 2). Along with this, the drought frequency has distinctly changed before and after 2000 (Figure S2). For this, we calculated the frequency of drought years in two sub-periods (1987–2000 and 2001–2017), illustrated in Figure 3. The averaged frequency of the SPEIs (1, 3, 6 and 12) for summer maize in the western, central and eastern regions increased by 13%, 6% and 7% with a standard error of ±0.046, ±0.023 and ±0.024, respectively, from 1987–2000 to 2001–2017 (Figure 3a,c,e). The frequency bars of winter wheat also revealed an increased frequency of drought years in the western, central and eastern regions by 12.5%, 7.5% and 8% with a standard error of ±0.037, ±0.025 and ±0.023 respectively between 1987–2000 and 2001–2017 (Figure 3b,d,f). The drought frequency in the western region is twice as high compared to the central and eastern regions after 2000 (Figure 3). The SPEI12 during the cropping season of winter wheat with a frequency of 0.08 during the first period increased remarkably to 0.25 during the second period in the central region (Figure 3d). Overall, the results reveal that the frequency of drought is simultaneously increasing in Nepal with the number of dry months during the recent decade.

**FIGURE 3** Fractional frequency of the Standardized Precipitation Evapotranspiration Indices (SPEIs) for summer maize and winter wheat in different regions ((a), (b) western, (c), (d) central and (e), (f) eastern) during 1987–2000 and 2001–2017. The orange bar represents the standard error.
3.3 | Evolution of SYRS

The linear trend of the summer maize and winter wheat in western, central and eastern regions exhibits a significant increment in yield from 1987 to 2017 (Table 4). The average yield of summer maize and winter wheat is higher in the central (2.10 tons·ha⁻¹, 1.99 tons·ha⁻¹) and eastern regions (2.10 tons·ha⁻¹, 1.85 tons·ha⁻¹) than the western region (1.85 tons·ha⁻¹, 1.73 tons·ha⁻¹) of the country. In particular, the lower belt (Terai) of the eastern and central regions is known as the grain basket of Nepal (Bourai et al., 2002). The simultaneous influence of various factors, such as technology enhancement, human resources, manure use, change in cropping pattern, use of crop varieties and weed control may produce an increment in agricultural yield. The yield time series were detrended; meanwhile, the SYRS shows the year-to-year variability of the climatic yield over the different regions of Nepal (Figure 4).

Frequent yield loss of summer maize and winter wheat is observed between 1987 and 2017 when drought episodes coincided (Figure 4). For instance, extreme yield loss (SYRS ≤ −1.5) years for winter wheat and summer maize were 2008/2009 and 2010, respectively, which were related to drought years. In contrast, an opposite variation pattern was observed for a few dry years, which may be related to rational allocation of water resources and progress in drought resistance activities. The yield loss years of winter wheat were found to be relatively fewer than those of summer maize across the country after 2000. It is also worth noting that the summer maize and winter wheat display opposite yield variability, that is, when summer maize exhibits a high yield increment, winter wheat exhibits a higher yield loss and vice versa, except for a few years.

To investigate the possible reason for crop yield failure in 2008 (winter wheat) and 2010 (summer maize), we further analysed the different lags of the SPEI from January to December in the western region of Nepal (Figure S3). The SPEI displays a drought during the summer maize cropping season (February–June, the period for sowing and growing) at 1–6 timescales in 2010, and at 1–6 timescales in 2007/2008 for the winter wheat cropping season (December of the previous year to May of the following year). These phenomena clearly explain the reason for selecting the exact cropping season for drought analysis of summer maize and winter wheat. Furthermore, the short-term and medium-term drought at 1–6 timescales accurately capture moisture deficiency in both the summer maize and winter wheat cropping season. Thus, there is a significant advantage of using short-term and medium-term timescales for agricultural drought impact analysis.

3.4 | Correlation between the SYRS, SPEI and soil moisture

The correlation coefficients between the monthly detrended SPEI time series at 1–12 month lags and the SYRS of summer maize and winter wheat from 1987 to 2017 are shown in Figure 5. The cropping period for summer maize ranges from February to September of the current year (Figure 5a,c,e). Here, a positive correlation indicates drought conditions which considerably influence the crop yields. Furthermore, the year-to-year variations of the SYRS (i.e. crop yield) are related to the year-to-year variations of the detrended SPEI time series. The highest correlation was observed during the sowing period of summer maize in all three regions. This indicates the most sensitive period for summer maize to water deficit, which may cause a considerable yield loss. The negative correlation during the harvesting period indicates that drought has no impact on the crop yield. Meanwhile, the correlation coefficients between the SYRS and SPEI during March–April at 2–6 month lags are consistently above 0.28, indicating that crop yield failure is related to the spring drought. Comparatively, a higher positive correlation was observed in March, April and May in the western region than in the central and eastern regions of the country (Figure 5a).

The correlation period for winter wheat ranges from December of last year to May of the current year (Figure 5b,d,f). The result shows a sensitivity of the winter wheat yield at different lags, indicating that the whole wheat cropping season is under the risk of drought. However, the highest positive correlation was observed during the growing period of winter wheat in all three regions at 1–5 month lags, indicating the most sensitive period to soil moisture deficit for winter wheat, which may cause a considerable yield loss. A positive relation of drought was also observed in the harvesting period of the winter wheat. Furthermore, the correlation coefficients between the SYRS and SPEIs between December and February at 1–5 month lags are above 0.20, indicating that crop yield failure is related to the winter drought. It also shows that a positive correlation (R < 0.10) at medium- and long-

| Region    | Summer maize | Winter wheat |
|-----------|--------------|--------------|
| Western   | 0.045 (p < .05) | 0.028 (p < .05) |
| Central   | 0.043 (p < .05) | 0.040 (p < .05) |
| Eastern   | 0.042 (p < .05) | 0.031 (p < .05) |
term drought can have an impact on the cropping cycle of wheat, especially in the central and eastern regions (Figure 5d,f).

Water deficiency in the soil due to high evapotranspiration creates a drought that results in water stress to the plant (Liu et al., 2018). The variability of precipitation/temperature affects the moisture content in the soil, causing water deficit and thus resulting in yield loss. Thus, the soil moisture at different cropping stages plays an important role in crop yield and production. The high correlation of soil moisture and yield in the sowing period of summer maize is observed with values of $R > 0.34$ across the country (Figure 6a). However, the correlation was found to be decreased for the growing and harvesting seasons (Figure 6c,e). The result justifies the previous finding that the highest moisture demand is during cultivation, germination, physiological maturity and growth of summer maize (Chen et al., 2016; Potopová et al., 2016).

The SYRS of winter wheat is significantly correlated ($R > 0.3$, $p < .05$) with the soil moisture in the growing season (Figure 6d). Similarly, the wheat yield in the central and eastern regions also shows a positive relation to the sowing period (Figure 6b) but of non-statistical significance. The statistically positive relationship in the growing period illustrates the most critical period for soil water requirement and causes a considerable gain in yield. The plants need high soil moisture in the reproductive phase, and drought occurrences during this stage cause yield loss (Chen et al., 2016; Potopová et al., 2016). Thus, the crop yield losses due to drought can be reduced if we can maintain soil moisture at the sowing period and growing period of summer maize and winter wheat, respectively, over three different regions of Nepal (Figure 6). Further, this supports the above finding that spring and winter drought can create water stress, resulting in a decreased yield of summer maize and winter wheat, respectively (Figure 5).

### 3.5 Changes in the relation between the SYRS and SPEI

The correlation between the SYRS and the detrended SPEIs of summer maize and winter wheat shows the variation between two sub-periods (1987–2000 and 2001–2017) (Figure 7). The correlation coefficient between the yield of summer maize and the detrended SPEI at 1 month lag increased from 1987–2000 to 2001–2017 in all three regions (Figure 7a). In contrast, an opposite variation pattern was observed for the 12 month lag SPEI for the central and eastern regions (Figure 7d). Further, the relation of the seasonal SPEI (SPEI3 and SPEI6) with the SYRS is negative (positive) in 1987–2000, and changed to positive (negative) in 2001–2017 for the western and central regions (eastern
The result demonstrates that the cropping period of summer maize was consistently influenced by drought in the second time period (2001–2017) in the central and western regions. Furthermore, meteorological drought (SPEI1) had an influence on crop yield in all three regions, whereas agricultural drought (SPEI3 and SPEI6) only had an influence in the western and central regions during the second period. The long-term water-deficient condition (SPEI12) can impact the yield of summer maize only in the western region of Nepal (Figure 7d).

The drought at different lags in the cropping period of winter wheat shows opposite correlations during the first (1987–2000) and second (2001–2017) period over the three different regions (Figure 7e–h). The SPEIs in the central and eastern regions show negative correlations during the first period (1987–2000) and positive correlations during the second period (2001–2017). In contrast, the correlation is positive in the first period and negative in the later period over the western region. This indicates that winter wheat production in the eastern and central regions was at higher risk of drought than the western regions in recent years. Furthermore, the short-term, medium-term and long-term drought risk is decreased in the cropping period of winter wheat in the western region, whereas it is significantly increased in the central region (Figure 7b,c).
**FIGURE 6** Spatial correlation between detrended soil moisture at different cropping stages and the Standardized Yield Residual Series (SYRS) of summer maize and winter wheat over (a), (b) western, (c), (d) central and (e), (f) eastern regions during 1987–2017, using ERA5 reanalysis datasets. The dotted points inside the map represent the significance at a 95% confidence interval.

**FIGURE 7** The correlation between the detrended Standardized Precipitation Evapotranspiration Indices (SPEIs) and Standardized Yield Residual Series (SYRS) for summer maize and winter wheat during 1987–2000 and 2001–2017. *, significant at $p < .05$. 
and eastern regions. These results are consistent with the results concluding that the frequencies of drought have significantly increased in the central and eastern regions of Nepal after 2000 during the cropping period of winter wheat (Figures 2b,d,f, and 4). Overall, the findings reveal that the summer maize yield of western and central regions and the winter wheat yield of central and eastern regions is at considerable risk of agricultural drought in recent years.

4 | DISCUSSION

Agriculture in Nepal contributes to ~27% of Nepal’s total GDP (Pokharel, 2019). The spatio-temporal variation of precipitation and temperature across the country favours the formation of seasonal and annual drought. Such droughts have an impact on crop yield, overall affecting the GDP and livelihood of people (Maharjan and Joshi, 2013; Prabnakorn et al., 2018). This study attempts to analyse the drought pattern and its impact on the cropping cycle of summer maize and winter wheat over three different regions of Nepal during 1987–2017. The time series of the SPEIs at cropping season show the development of dry and wet conditions at 1–12 month lags, representing drought characterization: severity, extent and duration (Lloyd-Hughes, 2012). Spatially, the SPEIs at different lags show that the western region has a slightly higher frequency of drought compared to the central and eastern regions. Previous studies also revealed increased drought over the western region (Sigdel and Ikeda, 2010; Wang et al., 2013; Kafle, 2015). Moreover, a negative Vegetation Condition Index trend was observed over the western region during 1982–2015, indicating the vulnerability of potential droughts (Baniya et al., 2019). Among different drought studies, Wang et al. (2013) have discussed frequent occurrences of winter drought since 2000 and the mechanism of drought formation in western Nepal, linking it to ocean–atmospheric circulation.

Summer precipitation decreases from east to west, with the highest in the central region (Kansakar et al., 2004; Talchabhadel et al., 2018). In contrast, the westerly disturbances in the winter season contribute a higher precipitation to the western region than the central and eastern regions of the country (Kansakar et al., 2004; Ichiyanagi et al., 2007; Wang et al., 2013). The recent study of annual precipitation distribution shows a notable decrease in annual precipitation in western Nepal and an increase in eastern Nepal (Pokharel et al., 2019). Meanwhile, an increasing trend of temperature has been observed recently over different regions of the country (Shrestha et al., 1999; Khatiwada et al., 2016; DHM, 2017; Thakuri et al., 2019). This might be the reason for the heterogeneous distribution of drought frequency and intensity across the country, resulting in increased drought risk for rain-fed crops. Similarly, Chen et al. (2016) also reported an increased drought due to changes in precipitation and temperature, affecting rain-fed crops (maize, sorghum, soybean and millet) in China.

The linear trend of the annual crop yield of the rain-fed crops summer maize and winter wheat is increasing across the country. However, yield loss has been mainly observed between 1987 and 2017. This might be related to the frequent occurrences of drought in 1992, 1994, 1996, 2001, 2006, 2008, 2009 and 2015, which were triggered by deficient precipitation (Wang et al., 2013; Dahal et al., 2015; Adhikari, 2018; Hamal et al., 2020b). For instance, the national production of major food crops (barley and wheat) dropped by 15% in 2008/2009 due to severe drought (World Food Programme, 2009). Similarly, the recent summer drought in 2015 caused food insecurity in Nepal, affecting more than 80% of the population in the western region (Gyawali, 2016).

The critical feature of the current study is to analyse the drought during the crop growing season and stages. The correlation of the drought with yield during the actual cropping season of summer maize and winter wheat was considered instead of the whole annual calendar (January–December), as in previous studies, to avoid uncertainties in an over-wintering crop like wheat (Potopová et al., 2015; Liu et al., 2018). The results show that the summer maize is more sensitive to drought in the sowing period than the growing period in Nepal. Our finding agrees with Liu et al. (2018) that the silking stage (initial reproductive stage) of the maize is highly susceptible to drought conditions in North China. However, the highest correlation of winter wheat was observed during the growing stage in short time lags of the SPEI. Furthermore, the highest correlation during the sowing and growing period is indicative of the highest moisture demand during cultivation, germination, physiological maturity and growth (Chen et al., 2016; Potopová et al., 2016). In these two stages, lower and excess soil moisture can adversely affect the crop production of the summer maize and winter wheat. The higher water availability (soil moisture) during the vegetative stage of the maize probably contributes to high yield (Daryanto et al., 2016). The wheat yield loss is higher when droughts are experienced in the reproductive or seed germination phase, reducing seed robustness by limiting soil moisture availability (Fahad et al., 2017; Hussain et al., 2018). Meanwhile, the soil moisture is comparatively low in the winter season affecting crop yield, which is in line with the high correlation coefficient of soil moisture and vegetation drought indices observed in October, November and February (Zhang et al., 2017).
The negative correlation of drought during the harvesting period as an indication of soil water availability may not be related to crop yield. Besides, a positive correlation was observed with medium- and long-term drought in the central and eastern regions for wheat. This can be related to medium- to long-term water deficits (Potop et al., 2014; Liu et al., 2018).

The drought has increased recently in Asian countries, and rain-fed crops are facing challenges from soil moisture stress (Miyan, 2015). A drought study during the crop phenology of wheat over India showed an increased frequency of drought in every decade (Zhang et al., 2017). Our study also shows an increased sensitivity of seasonal drought on the crop yields of summer maize in the western and central regions during the second decade (2001–2017). Furthermore, the drought sensitivity decreased in the western region whereas it increased in the central and eastern regions, respectively, for winter wheat. Recent climate change has impacted all seasons, but the warming rate is higher in the winter season than in summer (Shrestha et al., 1999; Kreyling et al., 2019). Similar to Nepal, a spatial–temporal variation of drought was observed in different regions of China (Yang et al., 2013; Tan et al., 2015; Shen et al., 2017) and had significant impacts on crop yield (Chen et al., 2016; Liu et al., 2018). Therefore, for successful cultivation and better yield of summer maize and winter wheat, an effective irrigation plan or a drought-resilient variety of seeds is required.

Moreover, the drought impact on crop analysis in the present study considers only climatic variability conditions, without anthropogenic influences. For example, drought sensitivity decreased in the eastern region and western region for summer maize and winter wheat, respectively, in the recent decade, which may be related to irrigation use and changes in crop varieties by farmers to cope with the drought. Further studies should include information about irrigation and adaptive measures for a detailed analysis of the relationship between drought and crop yield.

5 CONCLUSION

This study presents the spatio-temporal evolution and frequency of drought in the cropping season of cereal crops (winter wheat and summer maize) during 1987–2017 using an index that includes precipitation and potential evapotranspiration in the calculation (i.e. the Standardized Precipitation Evapotranspiration Index, SPEI), in three different regions of Nepal. Drought impact on summer maize and winter wheat yields was also examined. The results show frequent occurrences of severe drought episodes (1992, 1994, 2006, 2008, 2009, 2012 and 2015) during the cropping cycle of summer maize and winter wheat. Moreover, drought frequency has changed from 1987–2000 and 2001–2017. The averaged frequency for the SPEIs (1, 3, 6 and 12) of drought years for summer maize (winter wheat) in the western, central and eastern regions increased by 13% (12.5%), 6% (7.5%) and 7% (8%), respectively, from 1987–2000 to 2001–2017. Over the second period (2001–2017), the drought risk in the western region increased twofold compared with the central and eastern regions. The detrended Standardized Yield Residual Series (SYRS) shows the year-to-year variations in yield of both summer maize and winter wheat; frequent yield loss is experienced when drought episodes have occurred simultaneously.

The most correlated crop growth periods for summer maize and winter wheat with the SPEIs were the sowing and growing period, respectively, indicating the sensitive period of water deficit. Moreover, soil moisture over different regions shows that spring and winter drought can create water stress, resulting in a decreased yield of summer maize and winter wheat, respectively. Furthermore, to observe the changes of drought impacts on crop yield, the correlation between the SYRS (summer maize and winter wheat) and the detrended SPEI was carried out in two sub-periods (1987–2000 and 2001–2017). The correlation for summer maize with seasonal drought (SPEI3 and SPE6) increased for the western and central regions and substantially decreased for the eastern region in the second decade. In contrast, a significantly increased sensitivity to drought was observed in the central and eastern regions, with a decrease in the western region, during the cropping period of winter wheat.

The results suggest that drought has occurred in different cropping stages and ultimately affected the crop yield over different regions of Nepal. Although the results only consider climate variability conditions, they lead to an improved understanding of drought evolution in Nepal and hence provide stakeholders with references to design future drought mitigation plans.

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CONFLICT OF INTEREST
The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS
Kalpana Hamal developed the concept and wrote the original draft. Shankar Sharma, Nitesh Khadka, Gebremedhin Gebremeskel Haile, Bharat Badayar Joshi, Tianli Xu and Binod Dawadi contributed to writing, reviewing and improving the manuscript. Kalpana Hamal compiled all the figures and analysis with significant help from Shankar Sharma and Nitesh Khadka.

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Additional supporting information may be found online in the Supporting Information section at the end of this article.

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