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Estimating and Analyzing the Spatiotemporal Characteristics of Crop Yield Loss in Response to Drought in the Koshi River Basin, Nepal

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Abstract

The quantitative assessment of crop yield loss in response to drought is crucial in the development of the agricultural sector to improve the productivity. This study estimated and analyzed the spatiotemporal patterns of crop yield loss in response to drought using the Lagrange interpolation method, wavelet analysis, and sequential Mann-Kendall test in the mountain, hill, and Terai (low-land) regions of Nepal's Koshi River Basin from 1987 to 2016. According to the findings, average crop yield loss was common after 2000, with the Terai, hill, and mountain experiencing the greatest loss in maize, rice, and wheat, respectively. Average annual rice and wheat yield losses rate were highest in the mountains, while maize yield losses were highest in the Terai. There was an abrupt change in wheat yield loss in the mountain, with significant increasing trend. In the hill, significant increment in maize and wheat yield loss, and decrement in rice yield loss, were observed. Between 1987 and 2016, periodic variations of maize, rice, and wheat revealed significant yield loss after 2000. The characteristics of the first and second key periods for crop yield loss demonstrated variation period which predicted that crop yield loss would either enter high yield loss or low yield loss period shortly after 2016. The findings of the study provide a detailed intervention in assessing crop yield loss at the river basin level and can provide an important pathway for developing a crop yield loss mitigation plan in the agricultural sector to achieve self-reliance and sustainable agricultural productivity.

Keywords: Drought; Wavelet Analysis; Yield Loss Characteristics; Koshi River Basin

1 Introduction

Agriculture is one of the most apparent sectors to climate extremities such as drought. Despite the advancement of modern technology, climate and weather have always been uncontrollable factors influencing agricultural production (Lobell and Field 2007). According to global studies, drought conditions will become more persistent and widespread in the coming decades as a result of climate change (Dai 2011; Trenberth et al. 2014). Crop yield loss can occur because of several abiotic and biotic factors including climate, drought and crop diseases (Savary et al. 2006). Drought is a major abiotic factor that affects the crop yield and is expected to affect the growth in over 50% of the total arable land worldwide by 2050 (Vinocur and Altman 2005; Naveed et al. 2014). It is estimated that global cereal production will decline by 10.1% on average, 19.9% in Australia, North America and Europe, 12.1% in Asia and 9.2% in Africa (Lesk et al. 2016). The global estimation of actual crop production losses has been studied (Cramer 1967; Oerke et al. 2012). Crop yield loss due to drought, on the other hand, is complex due to its changing nature depending on drought characteristics in different growing stages (Potopová et al. 2016). Therefore, several studies agreed that quantifying and analyzing crop yield loss is difficult (Savary and Willocquet 2014; Cerda et al. 2017; Oerke 2006). Crop yield loss assessment quantifies yield loss and is the difference between the expected (ideal) yield and the actual yield (Nutter Jr et al. 1993). The expected yield is the maximum yield obtained in the absence of any disasters and with the best available agricultural inputs and techniques (Yu and Zhang 2009; Cerda et al. 2017). The term "actual yield" refers to the yield obtained from resources, which can be influenced by different abiotic and biotic factors (Cerda et al. 2017; Chandio et al. 2019). Along with the application of agricultural technologies, crop protection methods are changing, which must support to increase crop yield to meet future food demand caused by rising population (Oerke 2006; Van Ittersum et al. 2013). So, the current crop producing land must produce a higher yield than it currently does. Some regions have higher potential for crop yield due to favorable abiotic and biotic factors, whereas yield levels in other regions are lower than the national average (Van Ittersum et al. 2013). So, under ideal conditions, there is a yield gap (yield loss) between the current (actual yield) and theoretically achievable (expected yield). Therefore, to achieve the sustainable agricultural intensification, it is crucial to develop comprehensive knowledge about the yield loss (Van Ittersum et al. 2013).

As previously stated, agricultural productivity is highly sensitive to drought because it is directly related with water availability (Hanjra and Qureshi 2010). Although each crops has a different threshold and level of resilience to water deficit, drought can cause yield loss if it occurs in crop's sensitive growth stage (Lobell and Field 2007; Lobell et al. 2011). As a result, the drought can exacerbate agricultural losses, leading to food insecurity and famine. Tilman et al. (2011) stated that due to rising population, global food demand is expected to double by 2050, necessitating a 2.4 % increase in crop yield per year to meet this demand. So, the drought-related yield loss may be one of the major threats in achieving this demand in the future (Field et al. 2012). Therefore, an assessment of trend and change point detection on the historical series of crop yield loss is important to carry out in spatial and temporal scale to consider the inclusive knowledge about the yield loss (Kim et al. 2019).

Agriculture is a key economic and livelihood activity in developing countries such as Nepal, where over 75% of the total rural population relies on rainfed agricultural activities. Therefore, impact of any type of water hazards such as drought on these activities is very much crucial to their livelihood (Chapagain and Gentle 2015). The historical drought event substantially observed during the 1970s, 1980s, 1990s and after 2000 because of the uneven and less precipitation was extremely critical for the agricultural productivity and livelihood support for farming communities in Nepal (Adhikari 2018). During those periods, the eastern part of Nepal was affected by drought and suffered significant crop losses (UNDP and BCPR 2013). The Koshi River Basin (KRB) is one of Nepal's largest river basins, located in the country's eastern part. A study revealed that the basin's mean temperature is increasing by 0.2 ºC per decade, precipitation is erratic (Shrestha et al. 2017) and is thus extremely vulnerable to the drought (Chen et al. 2013). As 70% of the population depends on in the rainfed agriculture in the basin, the changing climate impact, especially drought, is having an impact on the basin (Dixit et al. 2009). Several studies on climate, water resources, and agriculture have been conducted in the basin (Agarwal et al. 2014; Agarwal et al. 2016; Bharati et al. 2019; Bhatt et al. 2014; Neupane et al. 2013) but none of these studies mentioned about the time series quantification of the crop yield loss, their changing trend and pattern in drought. Therefore, this study aims to (a) quantify the crop yield loss of rice, maize, wheat in the different regions - mountain, hill, Terai (low land) of the basin from 1987 to 2016 (b) identify the trend and turning point of the crop yield loss in mountain, hill and Terai region during 1987 to 2016 and (c) investigate the characteristics of crop yield loss variation at different timescales in mountain, hill and Terai regions from 1987 to 2016. The novelty of this study is to understand the interannual variation and characteristics of crop yield loss and its future prediction. This study can help policymakers and stakeholders design plans for future sustainable agricultural intensification by identifying spatial temporal characteristics of agricultural losses and quantifying them.

2 Materials and Methods

2.1 Study Area

Koshi River Basin is a transboundary river basin that is originated from the southern part of the Tibet (China) and enters the northern part of Bihar (India) passing through Nepal (Hussain et al. 2018). It has a total area of 87,311 km^2 covering 33% in China, 45% in Nepal, and 22% in India. In Nepal, the basin is divided into three major regions, namely the mountain, hill, and Terai with an altitudinal range from 60m to 8848.86m from the south to the north covering 27 districts. The entire basin has a population of 40 million and are mostly depended on the subsistence agriculture for the livelihood (Neupane et al. 2015). The basin has total 3.4 million hectare (ha) arable land and maize, rice, wheat are the major food crops produced. Maize is produced in 32%, rice in 61% and wheat in 23% of the total arable land (Neupane et al. 2015). The KRB Nepal had a population of about 11.7 million in 2011 and would be 13.2 million by 2017 (Hussain et al. 2018). Over 50% of the arable land is rainfall based and thus is sensitive to rainfall variation. The rainfall variation can create too low water, which directly affects the agriculture and water dependent livelihood.

Fig. 1 Geographical location of Koshi River Basin in Nepal with the mountain, hill, Terai districts of the basin, and the studied districts with weather stations.

2.2 Data

2.2.1 Agricultural Data

For this study purpose, the total annual yield data of maize, rice, and wheat were collected from the 16 districts in the KRB, Nepal from 1987 to 2016 (30 years). The data were collected from the Ministry of Agriculture and Livestock

Development, Government of Nepal. These data were considered as the actual crop yield data and were further analyzed to calculate the expected yield over the period from 1987 to 2016.

2.2.2 Climate Data and Drought Identification

The monthly minimum temperature, maximum temperature and precipitation data from the 23 meteorological stations covering the selected 16 districts in the KRB, Nepal (Figure 1) were collected for from 1987 to 2016 from the Department of Hydrology and Meteorology, Government of Nepal. The raw climate data were further analyzed to identify drought in the regions of KRB. The commonly used Standardized Precipitation Evapotranspiration Index (SPEI) method developed by Vicente-Serrano et al. (2010) was applied to identify the drought using R software (SPEI package version 1.7) (R Core Team 2020). The SPEI calculation requires monthly precipitation and temperature data as inputs. The monthly temperature is further used to estimate monthly potential evapotranspiration (PET). The difference between precipitation and PET provides the climatic water balance and is used to calculate SPEI. In this study, we used Hargreaves method to calculate PET (Hargreaves and Samani 1985) which has already been successfully applied in Nepal (Aadhar and Mishra 2017; Dahal et al. 2016; Bhatt et al. 2014; Penton et al. 2016; Hamal et al. 2020; Dahal et al. 2021).

The SPEI index at different timescales (1 to 12-month lags) were calculated for the growing season months of maize (March-August), rice (June-November) and wheat (November-May) from 1987 to 2016. The growing seasons for these crops were identified from several literatures and verified through the field visit (Nayava et al. 2009; Paudyal et al. 2001; Ghimire et al. 2012). The SPEI values in each region was obtained by averaging the SPEI-values at each meteorological station at 1 to 12-month lags for the crop growing seasons and identified the drought (Hamal et al. 2020; Liu et al. 2018; Potop et al. 2014). The drought categories defined by McKee et al. (1993) and Vicente-Serrano et al. (2010) has been illustrated in Table 1.

Table 1: Drought categories based on the SPEI values

SPEI Value	Categories
≥-0.99	Near Normal
-1 to -1.49	Moderate Drought
-1.5 to -1.99	Severely Drought
≤ -2	Extremely Drought

2.3 Lagrange Interpolation Method

Celik (2018b) mentioned that the interpolation is a mathematical function which estimates data for the unavailable measured data values from the set of measured values. The interpolation technique thus can be used in several sectors including the agriculture (Celik 2018a). So, in this study we applied Lagrange interpolation method to calculate the expected yield of maize, rice, and wheat in the mountain, hill and Terai regions of KRB, Nepal (Jeffreys et al. 1999; Celik 2018a; Yu and Xiu 2007). This method was firstly published by Waring in 1779, rediscovered by Euler in 1783 and published by Lagrange in 1795 (Jeffreys et al. 1999). The detail procedures of Lagrange interpolation method are:

Consider $x_1, x_2, \ldots x_n$ are the data in the time series, with their corresponding values $y_1, y_2, \ldots y_n$ with function $y = f(x)$ and a polynomial $p(x_i) = f(x_i)$; i= 0,1,2, …, n. The polynomial equation can be written as follows:

$$p(x) = a_0 + a_1 x + a_2 x^2 + ... + a_n x^n \tag{1}$$

for given (n+1) data points there are $x_0, x_1, ..., x_n$. For i = 0, 1, 2, ..., n at (n+1) number of points are illustrated as follows:

$$L(x) = \frac{(x - x_0)...(x - x_{i-1})(x - x_{i+1})...(x - x_n)}{(x_i - x_0)...(x_i - x_{i-1})...(x_i - x_{i+1})...(x_i - x_n)} \tag{2}$$

These polynomials are known as the Lagrange polynomials for $x_0, x_1, ..., x_n$ points with n^{th} degree and its sum is given as follows:

$$p(x) = f_0 L_0(x) + f_1 L_1(x) + f_2 L_2(x) + ... + f_i L_i(x) + ... + f_n L_n(x) \tag{3}$$

The p (x) is expressed as below and is known as the Lagrange interpolation

$$p(x) = \sum_{i=0}^{n} f_i L_i(x) \tag{4}$$

The Lagrange interpolating polynomial (LIP) of $p(x)$ which has (n-1) degree is passing through the n points (x_1, $y_1 = f(x_1)$), (x_2, $y_2 = f(x_2)$) ..., (x_n, $y_n = f(x_n)$), and is expressed as:

$$f(x) = \sum_{j=0}^{n} f_j(x) \tag{5}$$

$$f_j(x) = y_j \prod_{\substack{k=1 \\ k \neq j}}^{n} \frac{x - x_k}{x_j - x_k} \tag{6}$$

The equation can be written as:

$$f(x) = \frac{(x - x_2)(x - x_3)...(x - x_n)}{(x_1 - x_2)(x_1 - x_3)...(x_1 - x_n)} y_1 + \frac{(x - x_1)(x - x_3)...(x - x_n)}{(x_2 - x_1)(x_2 - x_3)...(x_2 - x_n)} y_2 + ... + \frac{(x - x_1)(x - x_2)...(x - x_{n-1})}{(x_n - x_1)(x_n - x_2)...(x_n - x_{n-1})} y_n \tag{7}$$

2.4 Estimation of Expected Crop Yield and Crop Yield Loss

Actual crop yield refers to the yield obtained after considering the actual effects of meteorological hazards, farm inputs, and other agricultural technological inputs, whereas expected crop yield refers to the yield obtained when there are no meteorological hazards (such as drought) and all of the favorable conditions required to achieve the maximum (expected) crop yield (Chandio et al. 2019). In this study, we estimated the expected yield of maize, rice, and wheat in the mountain, hill and Terai regions of the KRB, Nepal. For this, first we used the SPEI values to identify the meteorological hazards-free years from 1987 to 2016 during the growing seasons of maize, rice, and wheat in each region. SPEI-values ranging from -0.99 to 0.99 were considered normal (hazards-free) growing seasons for that year. The lower and higher the SPEI values between -0.99 and 0.99 indicate drought and wet conditions (Table1). Second, the maximum crop yield observed in the hazard-free years from 1987 to 2016 was considered as expected crop yield, assuming that the maximum yield is always expected and can be attained only if there is no hazards and all favorable conditions such as farm and agricultural inputs, are present. The Lagrange interpolation method was used to calculate expected yield for the remaining years between 1987 and 2016. The positive difference between expected yield and actual yield indicates a loss of yield.

2.5 Sequential Mann-Kendall Test

Sequential Mann Kendall test is the rank based non-parametric test used to analyze the potential abrupt change point in the timeseries of x_i (Sneyres 1990; Mohsin and Gough 2010). It considers the rank values $y_{i,}$ of all the terms in time series $x_1, x_2, x_3, \ldots, x_n$ to be analyzed. The magnitude of y_i =1, 2, 3, …., n is compared with $y_{j,}$ where y_j = 1, 2, 3, …., i -1. For each comparison, the cases where y_i is greater than y_j ($y_i > y_j$) are counted and represented by n_i. Then the MK rank statistic t_i is therefore expressed as (Bonfils 2012):

$$t_i = \sum_{j=1}^{i} n_i \quad (8)$$

When there is no monotonic trend under the null hypothesis, t_i has normal distribution with expected value of $E(t_i)$ and the variance var(t_i) is:

$$E\left(t_i\right) = \frac{i\left(i-1\right)}{4} \quad (9)$$

$$Var\left[t_k\right] = \frac{i\left(i-1\right)\left(2i+5\right)}{72} \quad (10)$$

Based on above assumption, the sequential values of standardized variables known as $u\left(t_i\right)$ statistic index is estimated for each of the test static variable t_i is:

$$u\left(t_i\right) = \frac{t_i - E\left[t_i\right]}{\sqrt{\operatorname{var}\left[t_i\right]}} \quad (11)$$

The forward sequential statistic, $u(t_i)$ is calculated by using the original time series data $x_1, x_2, \ldots, x_n$ and the backward sequential statistic, $u'(t_i)$ are estimated using the same process but starting from the end of time series. While estimating $u'(t_i)$ the timeseries data is rearranged so that the last series values come to the first $(x_1, x_2, \ldots, x_n)$.

The sequential Mann Kendall test provides the identification of approximate beginning of a developing trend. When $u(t_i)$ and $u'(t_i)$ curves are plotted, the intersection of these curves at certain point during the time interval shows the potential turning point. If this intersection occurs within ±1.96 (5% significance level) of the standardized statistic then a significant change at time interval is supposed. If at least one value of the standardized variable is greater than the chosen significance level, the null hypothesis is rejected.

2.6 Wavelet Analysis

Wavelet analysis is one of the useful tools to study the multi-scale analysis in different research field (Torrence and Compo 1998). This method is used to analyze multiple time scale features of the signal sequence by scaling and translating mathematical functions, and reflect local variations characteristics in time series data and has capacity to find out the turning point. In comparison with Fourier transform, this analysis is more effective in studying non-stationary time series data.

Torrence and Compo (1998) defined wavelet analysis by considering $\varphi(t)$ as a square-intangible function which is $\varphi(t) \in L^2(R)$ if its Fourier transform $\psi(\omega)$ satisfies the admissibility condition:

$$C_\varphi = \int_R |\psi(\omega)|^2 d\omega < \infty \tag{12}$$

Then, $\varphi(t)$ is called basic wavelet or the mother wavelet. The wavelet function $\varphi(t)$ must be scaled and translated to get a continuous wavelet (Labat 2010).

$$\varphi_{a,\tau}(t) = \frac{1}{\sqrt{a}} \varphi\left(\frac{t-\tau}{q}\right), a, \tau \in R, a > 0 \tag{13}$$

For any function $f(t) \in L^2(R)$, its continuous wavelet transform is defined as:

$$W_f(a,\tau) = \frac{1}{\sqrt{|a|}} \int_R f(t) \varphi\left(\frac{t-\tau}{a}\right) dt = \langle f(t), \varphi_{a,\tau}(t) \rangle \tag{14}$$

Where a is a scale factor, τ is time factor, $W_f(a,\tau)$ is the wavelet coefficient.

Morlet wavelet function is given by:

$$\Psi_0(\eta) = \pi^{-\frac{1}{4}} e^{iw_0\eta} e^{\frac{-\eta^2}{2}} \quad (15)$$

where, w_0 is the non-dimensional frequency

Wavelet variance is obtained by taking an integral of the square of wavelet coefficients in the same time domain

$$Var(a) = \int_{-\infty}^{\infty} \left|W_f(a,\tau)\right|^2 d\tau \quad (16)$$

Wavelet variance processes with scale τ can get map of wavelet variance which reflects the distribution of fluctuations with timescales in time series (Miao et al. 2012). Detail is explained in (Torrence and Compo 1998).

3 Results

3.1 Expected Crop Yield and Crop Yield Loss in the KRB

Figure 2 depicts a graphical representation of the actual and expected yields of maize, rice, and wheat in the mountain, hill, and Terai regions of KRB, Nepal, from 1987 to 2016. Overall, the graph explained the growing trend of both yields over time. For all the crops, the actual yield showed obvious year-to-year variation. However, some sharp fluctuations in the Terai region's maize yield after 2010 and the hilly region's rice yield before 1993. Table 2 depicts the hazard-free years with their respective maximum yields from 1987 to 2016 for all crops in the regions based on SPEI values.

Table 2: The hazard free years and maximum yield observed from 1987 to 2016; and Lagrange interpolating polynomials for estimating expected maize, rice, and wheat yield in the regions of KRB, Nepal.

Region	Crop	Hazard free years (x)	Maximum yield (y in kg/ha)	Lagrange interpolating polynomial
Mountain	Maize	1987	1639	$24.41x - 46858.52$
		2014	2298	
	Rice	1991	2251	$2.90x - 3532.38$
		2012	2312	
	Wheat	1998	1616	$41.80x - 81900.40$
		2003	1825	
Hill	Maize	1993	1796	$-1.50x^2 + 6060.05x - 6115546.48$
		2012	2751	
		2016	2814	
	Rice	1991	3193	$2.05x^2 - 8190.67 + 8175015.48$
		2005	3342	

		2015	3941	
	Wheat	1988	1469	$-0.01x^3+51.19x^2-99814.52x+64797571.86$
		2004	2438	
		2012	2674	
		2015	2712	
Terai	Maize	1991	2043	$3.16x^2-12556x+12464536.43$
		1993	2130	
		2014	4571	
	Rice	1991	2410	$-0.10x^2+425.22x-458399.29$
		2001	2777	
		2014	3225	
	Wheat	1990	1650	$-0.53x^2+2152x-2200631.83$
		2004	2394	
		2015	2834	

In the mountain region, the Lagrange interpolation polynomial for maize, rice, and wheat followed first-order polynomial, so the expected yield of these crops increased linearly from 1987 to 2016. Wheat had a sharp linear increasing trend in the region, followed by maize and rice, which had a slight increasing trend. The difference between expected and actual maize yield was observed to be greater from 1989 to 2007, and again in 2010 (Figure 2a). The rice yield gap is greatest between 1991 and 2012, with the smallest in 2005. (Figure 2b). The yield gap between expected and actual wheat yield was smaller from 1987 to 1998 and but it has been steadily increasing since after 2005. Lower and higher yield gaps represent lower and higher yield losses, respectively.

From 1987 to 2016, the expected maize and rice yields in the KRB's hill region followed a second order polynomial, while wheat yield followed a third order polynomial with a non-linear increment (Table 2). During the years 1987 to 1992, actual maize yield was slightly higher than the expected yield (Figure 2d). After 1992, the gap between expected yield and the actual yield widened, and the size of the gap fluctuated with the fluctuating actual yield. Prior to 1995, the expected rice yield in this region was not obvious (Figure 2e). During this period, however, the yield gap between expected and actual was observed greatest in 1987 and 1993. After 1995, the expected yield increased in accordance with the increasing actual yield trend. As a result, the yield gap has shrunk in comparison to before 1995. Figure 2f depicts the yield gap between expected and actual wheat yield. The wheat yield gap was greatest in 2009 and 2010, indicating significant yield loss.

Similarly, the LIP for expected maize, rice, and wheat yield in the Terai region followed a second order polynomial from 1987 to 2016, indicating a non-linear increment (Table 2). Actual maize yield increased sharply in 2014, widening the gap between expected and actual yield (Figure 2g). As a result, the yield gap was greatest from 2006 to 2011, 2015, and 2016. From 1987 to 2016, the yield gap between expected and actual rice yield fluctuated (Figure 2h). In 1987, 1995, 1999, 2007 and 2010, yield gaps were noticeably larger. Between 1987 and 2016, the expected wheat yield in the Terai region showed sharp increase (Figure 2i). The actual yield is also increasing, with fluctuations over several years. Therefore, the yield gap between expected and actual yield has been observed to be greater in several years, including 1993, 1999, and 2009.

The overall result shows that crop yield loss was greatest after 2000. During 1987 to 2016, the highest maize yield loss was observed in the mountain (429 kg/ha) and hill (611 kg/ha) in 2002, while in the Terai it was 1977 kg/ha in 2015. Similarly, the highest rice yield loss was observed in the hill (979 kg/ha), Terai (578 kg/ha) in 1987 and the mountain (624 kg/ha) in 2013. Similarly, the highest wheat yield losses were observed in the mountain (853 kg/ha) and hill (823 kg/ha) in 2010, while the loss in the Terai was 519 kg/ha in 1993. The overall pattern of average yield loss was Terai > hill > mountain for maize; hill > mountain > Terai for rice and mountain > hill > Terai for wheat.

Fig. 2 The actual and expected yield of maize, rice, and wheat yield from 1987 to 2016 in the mountain, hill and Terai regions of Koshi River Basin, Nepal.

Table 3 depicts the annual yield loss rate for maize, rice, and wheat. During 1987 to 2016, the highest annual yield loss rate for maize was observed in the Terai region (42.58%), rice in the hill region (29.69%) and wheat in the mountain region (40.3%) (Table 3). After 2000, the frequency of years with a higher yield loss rate (> 20%) for all the crops in regions was observed. From 2007 to 2010 and 2009 to 2016, the yield loss rate for rice and wheat in the mountain region was greater than 20% and 25% respectively. Wheat yield loss rate was greater than 30% in the hilly region in 2009 and 2010, while maize yield loss rate was greater than 20% in the Terai region from 2001 to 2012 and again from 2015 to 2016.

Between 1987 and 2016, the average maize yield loss rate was found to be 12.79 kg/ha (mountain), 10.01 kg/ha (hill), and 19.16 kg/ha (Terai). The average yield loss rate for rice was found to be 12.51 kg/ha (mountain), 10.43 kg/ha (hill), and 6.36 kg/ha (Terai). The average yield loss rate for wheat was determined to be 16.21 kg/ha (mountain), 12.18 kg/ha (hill), and 7.81 kg/ha (Terai). During 1987 to 2016, the mountain, hill and Terai regions had the the highest maize yield loss rates of 21.41% (2002), 25.65% (2002), 42.58% (2010), respectively. Similarly, the highest rice yield loss rates in these regions were found to be 26.97% (2013), 29.69% (1987) and 25.62% (1987) respectively. Similarly, the highest yield loss rates for wheat of 40.3% (2010), 31.17% (2010) and 28.43% (1993) were observed for the mountain, hill and Terai regions, respectively, from 1987 to 2016.

Table 3: The annual rate of maize, rice, and wheat yield loss from 1987 to 2016 in the mountain, hill, and Terai regions of Koshi River Basin, Nepal.

Year	**Mountain**			**Hill**			**Terai**		
	MYLR (%)	**RYLR (%)**	**WYLR (%)**	**MYLR (%)**	**RYLR (%)**	**WYLR (%)**	**MYLR (%)**	**RYLR (%)**	**WYLR (%)**
1987	0.00	20.72	15.42	-6.12	29.69	-1.05	2.14	25.62	-5.53
1988	14.30	13.02	15.15	-6.83	19.79	0.00	13.24	4.23	0.96

1989	16.03	7.00	10.81	-3.24	10.01	5.62	3.06	4.41	-1.99
1990	18.95	6.24	13.87	-7.81	9.51	6.33	3.99	1.16	0.00
1991	12.66	0.00	14.43	-7.46	0.00	10.96	0.00	0.00	4.12
1992	13.59	4.89	16.93	-3.04	13.01	18.36	2.82	-3.55	9.20
1993	17.25	10.41	12.47	0.00	26.83	21.56	0.00	8.21	28.43
1994	18.46	18.68	8.68	12.01	19.51	15.92	2.05	0.56	15.14
1995	17.83	22.42	8.31	12.28	19.13	18.96	13.88	15.05	16.00
1996	18.21	17.40	14.51	16.48	18.12	20.76	10.66	7.71	17.26
1997	18.52	16.70	9.25	20.88	16.92	19.02	13.50	6.00	14.61
1998	15.18	16.18	0.00	21.00	15.98	17.94	15.70	7.39	17.97
1999	21.37	13.43	22.89	19.95	12.68	23.55	20.78	16.80	22.77
2000	19.23	10.75	8.17	18.03	11.74	17.21	15.93	2.95	11.71
2001	16.67	8.94	1.46	19.02	10.56	16.81	24.72	0.00	10.00
2002	21.41	17.97	3.77	25.65	10.10	16.18	20.38	3.79	8.57
2003	14.44	8.44	0.00	14.62	-0.08	7.40	20.73	2.74	5.68
2004	17.01	8.55	2.61	19.40	0.46	0.00	23.94	-4.07	0.00
2005	15.79	2.47	3.54	22.20	0.00	4.01	30.06	-2.19	2.12
2006	16.37	13.47	13.74	18.88	2.97	11.98	30.75	5.94	8.10
2007	12.73	23.44	16.97	18.50	3.80	19.71	36.09	16.94	1.73
2008	5.64	20.30	18.22	14.09	3.89	19.15	38.84	9.42	2.87
2009	6.70	20.40	40.19	13.28	6.96	30.80	42.06	6.97	9.88
2010	16.38	24.45	40.30	12.60	11.87	31.17	42.58	15.12	6.78
2011	2.36	13.85	28.83	11.66	11.98	4.51	40.47	9.61	8.00
2012	3.65	0.00	32.61	0.00	5.62	0.00	20.87	-2.02	7.15
2013	2.84	26.97	28.19	18.12	5.31	2.70	13.88	9.73	3.00
2014	0.00	0.37	29.62	4.80	4.62	4.70	0.00	0.00	0.75
2015	6.03	0.45	28.43	1.46	0.00	0.00	41.56	10.28	0.00
2016	3.99	7.33	26.90	0.00	11.89	1.26	30.24	12.02	8.99

Note: MYLR: Maize Yield Loss Rate; RYLR: Rice Yield Loss Rate; and WYLR: Wheat Yield Loss Rate

Overall, the average yield loss rate of rice and wheat from 1987 to 2016 followed the pattern of mountain > hill > Terai, while maize followed the pattern of Terai > mountain > hill. During the period, the highest maize yield loss rate was observed in the Terai region, the highest rice yield loss rate in the hilly region, and the highest wheat yield loss rate in the mountain region. Similarly, in 1987, the hilly and Terai regions had the highest rice yield loss rate. The highest maize yield loss rate was observed in 2002 in the mountain and hilly region, while the highest wheat yield loss rate was observed in the mountain and Terai regions in 2010.

3.2 Abrupt changes of annual crop yield loss

Identifying the crop yield loss point is an important factor that can help provide a better interpretation and more accurate crop yield prediction. Figure 3 illustrates the abrupt changes points in the annual crop yield loss timeseries data from 1987 to 2016. During the period there were abrupt changes in the inter-annual variation of the crop yield loss in the mountain, hill, and Terai regions of the KRB. Figure 3a shows the abrupt changes in maize yield loss that occurred between 2013 and 2015, indicating a decreasing trend in the mountain region. Figure 3b suggests an intersection in rice yield loss in the mountain region in 1994, 2004, 2006, 2012, 2013, and 2014. The intersection showed a trend of increasing and decreasing yield loss. Figure 3c shows the increasing trend of wheat yield loss in the mountain since 2009, with a significant trend beginning in 2013 ($P < 0.05$).

Figure 3d suggests the intersection for maize yield loss in the hill region occurred in 1993, with a significant increasing trend after 1995 ($P < 0.05$). Figure 3e shows the abrupt change in rice yield loss in the hilly region in 1990, 1992, and 1998. After 1998, the change showed a decreasing trend that became statistically significant after 2002 ($P < 0.05$). Figure 3f shows abrupt change in wheat yield loss that occurred in the hill region in 1988 and 2015. The change in 1988 showed an increasing trend that remained significant after 1990 until 2004.

Figure 3g showed an abrupt change in maize yield loss in the Terai region in 2000 with an increasing trend. Figure 3h suggests the intersection in 2010 and 2011of a short, increasing trend in the Terai rice yield loss. Figure 3i shows the abrupt change in wheat yield loss in the Terai region in 2014, with a slight decreasing trend.

The overall results show that crop yield loss in the KRB's mountain, hill, and Terai regions fluctuated significantly from 1987 to 2016, with most of the changes occurring after 2000. An abrupt change occurred in the mountain region in 2009, followed by a significant increase in wheat yield loss after 2013. Maize, rice, and wheat yields in the hilly region showed abrupt changes and a significant trend. After 1993, maize yield loss increased, with a significant increase after 1995. Rice yield loss intersected in 1990, 1992, and 1998, and a decreasing trend was observed after 1998, which was significant after 2002. Wheat yield loss experienced abrupt changes in 1988 and 2015, with a significant increase in trend between 1990 and 1999.

Fig. 3 Graphical representation of the progressive series *u(t)* and retrograde series *u'(t)* of Sequential Mann-Kendall statistic test: (a-c) maize, rice and wheat yield loss in the mountain, (d-f) maize, rice and wheat yield loss in the hill and (g-i) maize, rice and wheat yield loss in the Terai regions of KRB, Nepal. The red dash lines are the upper and lower critical values (±1.96, $P = 0.05$), respectively.

3.3 Wavelet Analysis of crop yield loss

3.3.1 Analysis of Wavelet Transform

The wavelet coefficient's real contour map depicts the periodic variation of crop yield loss (maize, rice, and wheat) time series data (1987-2016) in various timescales (1 to 16 years). Figures 4a, 4e, 4i, 5a, 5e, 5i, and 6a, 6e, 6i show the real part of the yield loss in the mountain, hill, and Terai from 1987 to 2016. The pink zone represents the highest yield loss, the blue zone represents the lowest yield loss, and the other colors represent the intermediate loss.

As shown in Figures 4a, 4e, and 4i, maize yield loss varied from 4 to 12 years, rice yield loss varied from 10 to 16 years, and wheat yield loss varied from 8 to 16 years in the mountain region. There were over 3 cycle oscillations on the 4-12-year scale. Similarly, both the 10-16-year and 8-16-year scales had two cycle oscillations. The years 1990-1992, 2007-2008, and 2011-2012 showed high maize yield losses; 1987-1989, 1998-2001 witnessed high rice yield losses; and 1998-2003, 2007-2012 showed high wheat yield losses. Low maize yield periods occurred in 1987-1989, 1993-1994, 2009-2010, 2013, 2014-2015; low rice yield periods occurred in 1991-1995, 1999-2000, 2003-2005; and low wheat yield periods occurred in 2005-2006 and 2013-2014.

Fig.4 Wavelet coefficient contour map (a, e and i), wavelet variance diagram (b, f and j), major periodic oscillation at different timescale of maize, rice and wheat yield loss in the mountain region of the KRB, Nepal.

In the hilly region, maize yield loss varied over timescales of 4-7 years and 12-16 years; rice yield loss varied over timescales of 9 to 15 years; and wheat yield varied over timescales of 10 to 16 years, as shown in Figures 5a, 5e, and 5i. There were over 1 cycle oscillations on the 4-7-year scale and 2 cycle oscillations on the 12-16-year scale. Similarly, there were one and two oscillations on the 9-15-year scale and 10-16-year scale, respectively. High maize yield loss periods were 2010-2011, 2014-2015 (4-7-year timescale), 1987-1988, 1997-1999 (12-16-year timescale); high rice yield loss periods were 1987-1990, 1993-2000; and high wheat yield loss periods were 1999-2003, 2008-2012. Low maize yield loss periods were 2012-2013 (4-7-year timescale), 1991-1994, 2001-2004 (12-16-year timescale), and 2004-2007 and 2013-2016. Low rice yield loss periods were 1991-1994, and low wheat yield loss periods were 2004-2007 and 2013-2016.

Fig.5 Wavelet coefficient contour map (a, e and i), wavelet variance diagram (b, f and j), major periodic oscillation at different timescale of maize, rice and wheat yield loss in the hill region of the KRB, Nepal.

As shown in Figures 6a, 6e, and 6i, maize yield loss varied from 10 to 16 years, rice yield loss varied from 11 to 16 years, and wheat yield loss varied from 7 to 16 years in the Terai region. There were 2 cycle oscillations on the 10-16-year scale, 3 cycle oscillations on the 11-16-year scale, and over 3 cycle oscillations on the 7-16-year scale. High maize yield loss periods were 1998-2003, 2008-2012, and 2011-2012; high rice yield loss periods were 1987-1990, 1997-2001, and 2007-2011; and high wheat yield loss periods were 1987-1991, 1992-1996, 1999-2003, and 2009-2014. Low maize yield loss periods were observed in 2004-2007 and 2013-2016; low rice yield loss periods were observed in 1992-1995, 2003-2005, and 2013-2014; and low wheat yield loss periods were observed in 1989-1992, 1997-1999, 2005-2007, and 2013-2016.

Fig.6 Wavelet coefficient contour map (a, e and i), wavelet variance diagram (b, f and j), major periodic oscillation at different timescale of maize, rice and wheat yield loss in the Terai region of the KRB, Nepal.

The overall results of the wavelet transform analysis show that maize yield loss varied in two timescales (4-7-year and 12-16-year) in the hilly region, whereas it varied in one timescale in the mountain (4-12-year) and Terai (10-16-year) over a 16-year period from 1987 to 2016. Rice and wheat yield losses varied in one timescale in all three regions from 1987 to 2016 over the entire timescale. During 1987-2016, a high maize yield loss period was observed in several years until 2012 in the mountain and Terai, and in 2015 in the hill. During 1987-2016, the mountain had a high rice yield loss period until 2001, the hill had a high yield loss period until 2000, and the Terai had a high yield loss period until 2011. Similarly, from 1987 to 2016, a high wheat yield loss period was observed in the mountains and hills until 2012, and in the Terai until 2014.

3.3.2 Analysis of Wavelet Variance and Periodic Features

The wavelet variance figures showed the wave energy distribution with timescale (year) of the studied crop yield loss time series in various regions of the KRB, Nepal. It can identify the key period in the development process of a yield loss series. The annual crop yield loss series had two obvious peaks, as shown in Figures 4b, 4f, and 4j for mountain crops; 5b, 5f, and 5j for hill crops; and 6b, 6f, and 6j for Terai crops. The highest peak value observed at a particular timescale reflects the strongest cycle oscillation of timescale and is the first key period of crop yield loss variation. For instance, the highest peak value observed at timescale-8 for the maize in the mountain region corresponds to the strongest first key period of yield loss from 1987 to 2016. The second peak value corresponds to the second dominant period from 1987 to 2016. This demonstrates that the fluctuation of these two periods governs the variation features of the annual crop yield loss over the study time domain.

According to the results of the wavelet variance test, the wavelet coefficient process of the two-key period (timescale) of the crop yield loss time series evolution has been shown in Figure 4c-4d, 4g-4h and 4k-4l for the mountain; Figure 5c-5d, 5g-5h and 5k-5l for the hill and Figure 6c-6d, 6g-6h and 6k-6l for the Terai. Table 3 depicts the average period and variation characteristics in the evolution process of annual crop yield loss in the mountain, hill, and Terai regions over different timescales. Crop yield loss time series distribution characteristics from 1987 to 2016 in the entire study domain are uneven and have significant localization characteristics. The variation process of high and low yield loss under different timescale features is distinct and is closely related to timescale. As a result, the crop yield loss time series in all regions has two key timescale periods.

The overall results of the wavelet variance and periodic feature analysis showed that the first main period of maize and wheat yield loss varied for the mountain and Terai regions whereas for the rice yield loss the first main period was the same (11-year timescale). The characteristics of these timescales played an important role in the high and low yield loss variation trend in the crops in the regions of KRB. According to this characteristics scale, it can be predicted that the crop yield loss will enter the high yield loss or low yield loss period in a short time after 2016.

Table 3: Analysis results of crop yield loss timeseries characteristic in the different time scales

Region	Crop	Timescale	Variation period/year	Cycle Times	Crop yield loss variation trend after 2016	Reference
Mountain	Maize	8	6	5	Enter high yield loss period	Figure 1c
		4	3	10	Progressively entering high yield loss period	Figure 4d
	Rice	11	7.5	4	Progressively entering high yield loss period	Figure 4g
		5	3.75	8	Enter low yield loss period	Figure 4h
	Wheat	12	7.5	4	Enter high yield loss period	Figure 4k
		5	3.3	9	Enter low yield loss period	Figure 4l
Hill	Maize	6	4.28	7	Progressively entering low yield loss period	Figure 5c
		4	2.72	11	Enter low yield loss period	Figure 5d
	Rice	11	7.5	4	Enter low yield loss period	Figure 5g
		5	3	10	Enter low yield loss period	Figure 5h
	Wheat	13	10	3	Enter low yield loss period	Figure 5k
		6	3.75	8	Enter high yield loss period	Figure 5l
Terai	Maize	11	7.5	4	Progressively entering high yield loss period	Figure 5c
		3	3.33	9	Enter high yield loss period	Figure 5d
	Rice	11	7.5	4	Enter high yield loss period	Figure 5g
		6	4.28	7	Enter low yield loss period	Figure 5h
	Wheat	9	6	5	Enter low yield loss period	Figure 5k
		5	3.75	8	Enter low yield loss period	Figure 5l

4 Discussion

This study estimated and analyzed the yield loss of maize, rice and wheat in the mountain, hill and Terai regions of KRB from 1987 to 2016. In this study, we calculated the yield loss after estimating the expected crop yield using the Lagrange interpolation method. Second, the year in which abrupt changes in yield loss occurred during the time series was determined. Third, the periodic variation of crop yield loss time series data was identified in different timescales, and the key periods in the crop yield loss series development process were determined.

4.1 Analysis of Crop Yield Loss in the KRB, Nepal

Our findings revealed that the highest yield loss for the maize, rice, and wheat occurred after 2000, from 1987 to 2016. The occurrence of drought during this period may have resulted in yield loss in Nepal's Koshi River Basin. Dahal et al. (2021) discovered that moderate and severe droughts occurred frequently in the basin between 1987 and 2017. The overall pattern of average maize yield loss in our study is Terai > hill > mountain, rice yield loss is hill > mountain > Terai, and wheat yield loss is mountain > hill > Terai. The loss of maize, rice, and wheat yields in the Terai, hill, and mountain regions may be related to the spring, summer, and winter droughts. Dahal et al. (2021) investigated the drought phenomenon in the KRB, Nepal, and discovered that spring, summer, and winter droughts were prevalent in the Terai, hill, and mountain regions of the KRB, Nepal, respectively, from 1987 to 2017. Drought is one of the leading causes of crop yield loss, and its occurrence during growing seasons can have an impact on yield. Our yield loss findings are similar to those of Joshi (2018), who revealed that droughts in the eastern and central regions of Nepal in the 1990s (1992, 1994, and 1997) and 2000s (2002, 2008, 2009, 2012, and 2013) caused significant crop loss of approximately 0.385 million Metric Ton. From 1987 to 2016, the average yield loss rate for rice and wheat was mountain > hill > Terai, while maize was Terai > mountain > hill. The higher yield loss rate characteristics are attributed to the lack of agricultural intensification, adequate precipitation, and farming inputs, resulting in low yield, which can exacerbate food insecurity (Joshi et al. 2012). The major constraints for low rice yield are inappropriate technologies for rainfed agriculture, limited accesses to modern technology to minimize loss rate from abiotic factors such as drought (Tripathi et al. 2019). The higher maize yield loss in the Terai region could be attributed to the region's inappropriate seed variety in the changing climate, which increases food insecurity and profit loss. Thus, in Terai conditions, selecting hybrid maize may be appropriate for reducing yield loss (Ghimire et al. 2016). The higher wheat yield loss in KRB's mountain region could be attributed to sowing conditions, varietal selection, and varying climatic conditions such as drought (Thapa et al. 2020). Our findings showed that the mountain's wheat loss was 40.2% which is slightly lower than the findings of Thapa et al. (2020) which were 50-62% for the entire Nepal.

4.2 Abrupt Change in Crop Yield Loss

Our study for maize, rice, and wheat yield showed a series of losses in the mountain, hill, and Terai regions of KRB from 1987 to 2016. The pattern of losses during the period was revealed by the abrupt change analysis of these losses. Our findings revealed a significant increase in wheat yield loss in mountain and hilly regions. During 1987-2016, there was a significant increase in maize yield and a decrease in rice yield in the KRB's hilly region. The increase in mountain wheat yield loss observed in 2009 could be attributed to the winter droughts of 2008 and 2009, which reduced national wheat yield by 14.5% (WFP 2009). Similarly, the wheat yield loss change observed in the hilly region in 1988 and 2015, as well as the significant increasing loss trend between 1990 and 1999, could be attributed to a variety of abiotic factors such as drought and hailstone, which cause wheat yield loss in Nepal's hilly region (Pandey et al. 2020). The significant decrease in winter precipitation (10.9 mm/decade) in the hilly region of KRB from 1987 to 2017 may also have contributed to yield loss (Dahal et al. 2021). Similarly, Chatrath et al. (2007) discussed how the scarcity of improved seed varieties, inefficient water use, and a lack of climate resilient farming techniques can all contribute to wheat yield loss. The hilly region's maize yield loss was observed in 1993 and showed a significant increase after 1995. Maize is sown in the rainfed condition in the hilly region, so it is dependent on precipitation (Nayava 2010). The obvious poor distribution of precipitation in the 1990s (particularly in 1992, 1994 and 1997) in the eastern and central regions of Nepal may have contributed to a significant increase in maize yield loss in the hilly region (Joshi 2018). Rice yield loss intersected in 1990, 1992, 1998 and a decreasing trend was observed after 1998, becoming significant after 2002. The decreasing trend of rice yield loss may be due to improved technologies. Rice is cultivated without irrigation in terraced lands in the hilly region. Thus, several crop management practices and drought-tolerant varieties have been introduced to reduce the potential threat of yield loss due to abiotic stresses (Adhikari et al. 2015). Drought tolerant rice varieties introduced after 2001, as well as access to chemical fertilizers in the hilly region, may have reduced rice yield losses in the hilly region after 2002 (CDD and ASoN 2017).

4.3 Wavelet Analysis of crop yield loss

The wavelet transform analysis revealed the variation of maize, rice, and wheat yield loss at different timescales in the KRB's mountain, hill, and Terai regions between 1987 and 2016. Similarly, the results of the wavelet variance and periodic features analysis revealed the two dominant periods. Over the entire time domain, these two dominant periods control the changes in crop yield loss. The coefficient's process line depicts the high and low yield loss periods at different timescales. Table 3 shows the timescale, variation period (year), and number of cycles observed for the two dominant periods for maize, rice, and wheat yield loss in all KRB regions. Based on these, the next peaks of the dominant period timescale after 2016 can be projected, as shown in Table 4.

Table 4: Projection of the two dominant periods of crop yield loss timeseries characteristic in the different time scales

Region	Crop	Timescale	Variation period/year	Number of Cycle	Next peak after 2016
Mountain	Maize	8	6	5	2017 and 2023
		4	3	10	2017 and 2020
	Rice	11	7.5	4	2019 and 2026
		5	3.75	8	2019 and 2022
	Wheat	12	7.5	4	2019 and 2026
		5	3.3	9	2023 and 2026
Hill	Maize	6	4.28	7	2022 and 2026
		4	2.72	11	2020 and 2022
	Rice	11	7.5	4	2019 and 2026
		5	3	10	2017 and 2020
	Wheat	13	10	3	2017 and 2027
		6	3.75	8	2019 and 2022
Terai	Maize	11	7.5	4	2019 and 2026
		3	3.33	9	2023 and 2026
	Rice	11	7.5	4	2019 and 2026
		6	4.28	7	2022 and 2026
	Wheat	9	6	5	2017 and 2023
		5	3.75	8	2019 and 2022

The next peaks of the 11-year timescale (maximum first dominant period) for rice yield loss (all regions) and maize yield loss may occur around 2019 and 2026. (Terai). Similarly, the next 5-year timescale peaks (maximum second dominant period) for rice yield loss (mountain) and wheat yield loss may occur around 2019 and 2022. (Terai). Similarly, for wheat yield loss (mountain), 2023 and 2026 are observed, and for rice yield loss, 2017 and 2020 are observed (Hill).

5 Conclusion

In this study, spatial and temporal pattern of maize, rice, and wheat yield loss in the KRB, Nepal were estimated and analyzed between 1987 and 2016. The average crop yield loss (kg/ha) followed the pattern of the Terai > hill > mountain for maize; hill > mountain > Terai for rice and mountain > hill > Terai for wheat and is more significant after 2000. Similarly, the average yield loss rate for rice and wheat followed the mountain > hill > Terai pattern, whereas the maize yield loss rate was found to be Terai > mountain > hill pattern. The abrupt change in the mountain wheat yield loss occurred in 2009, and the trend has significantly increased since 2013. Similarly, while the abrupt change in wheat yield loss occurred in 1988 and 2015, the significant increasing yield loss trend was only observed between 1990 and 1999 in the hilly region. The abrupt change in maize yield loss in the hilly region was observed in 1993 which significantly increased after 1995. Despite the abrupt changes in 1990, 1992, and 1998, rice yield loss in the hilly region has shown a decreasing trend since 2002.

Between 1987 and 2016, the periodic variation revealed several high maize yield loss years until 2012 in the mountain and Terai and 2015 in the hill. Similarly, the high rice yield loss period was observed until 2001 in the mountain, 2000 in the hill and in the Terai until 2011. Likewise, the high wheat yield loss period was observed in the mountain and hill until 2012 and in the Terai 2014. The wavelet variance and periodic features showed that the first key period of the maize and wheat yield loss differed for the mountain and Terai regions, but not for rice yield loss. The 11-year timescale was the first critical period in all regions. The characteristics of these timescales played a significant role in the high and low yield loss variation trend in the crops in the KRB regions. According to this characteristics scale, it can be predicted that the crop yield loss will enter the high yield loss or low yield loss period in a short time after 2016.

The findings of this study revealed that the maize, rice, and wheat yield losses were prevalent in the KRB regions of Nepal between 1987 and 2016. The findings also showed a significant change in yield loss across timescales during the study period and predicted the occurrence of high or low yield loss after 2016. The findings of this study can help agriculturalists, agronomists and policy makers make detailed intervention in crop yield loss, economic analysis and future technical measures to increase productivity.

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Declarations

Data availability: Not applicable**.**

Code availability: Not applicable**.**

Conflict of interest: We have no conflict of interest to declare.

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Author Contributions

All authors contributed to this study. The first draft of the manuscript was written by Nirmal Mani Dahal and all authors revised and provided feedbacks on the manuscript. All authors read and approved the final manuscript. The details of contribution are as follows:

Conceptualization: Nirmal Mani Dahal, Donghong Xiong, Nilhari Neupane; Methodology: Nirmal Mani Dahal, Su Zhang; Formal analysis and investigation: Nirmal Mani Dahal; Writing - original draft preparation: Nirmal Mani Dahal; Writing - review and editing: Nilhari Neupane, Yong Yuan, Baojun Zhang, Yiping Fang, Wei Zhao, Yanhong Wu, Wei Deng; Funding acquisition: Donghong Xiong, Yanhong Wu, Wei Deng; Resources: Donghong Xiong; Supervision: Donghong Xiong.

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Figures

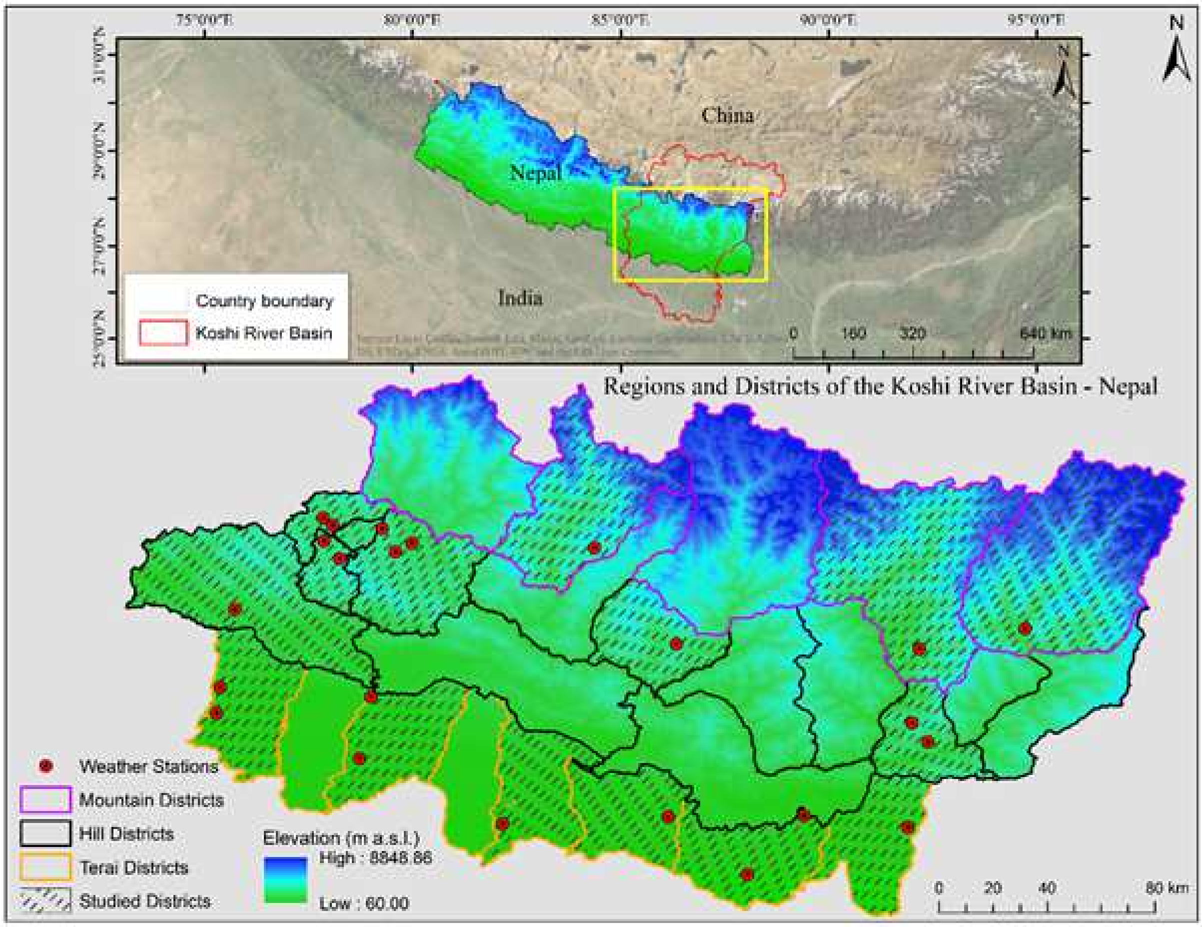

Figure 1

Geographical location of Koshi River Basin in Nepal with the mountain, hill, Terai districts of the basin, and the studied districts with weather stations.

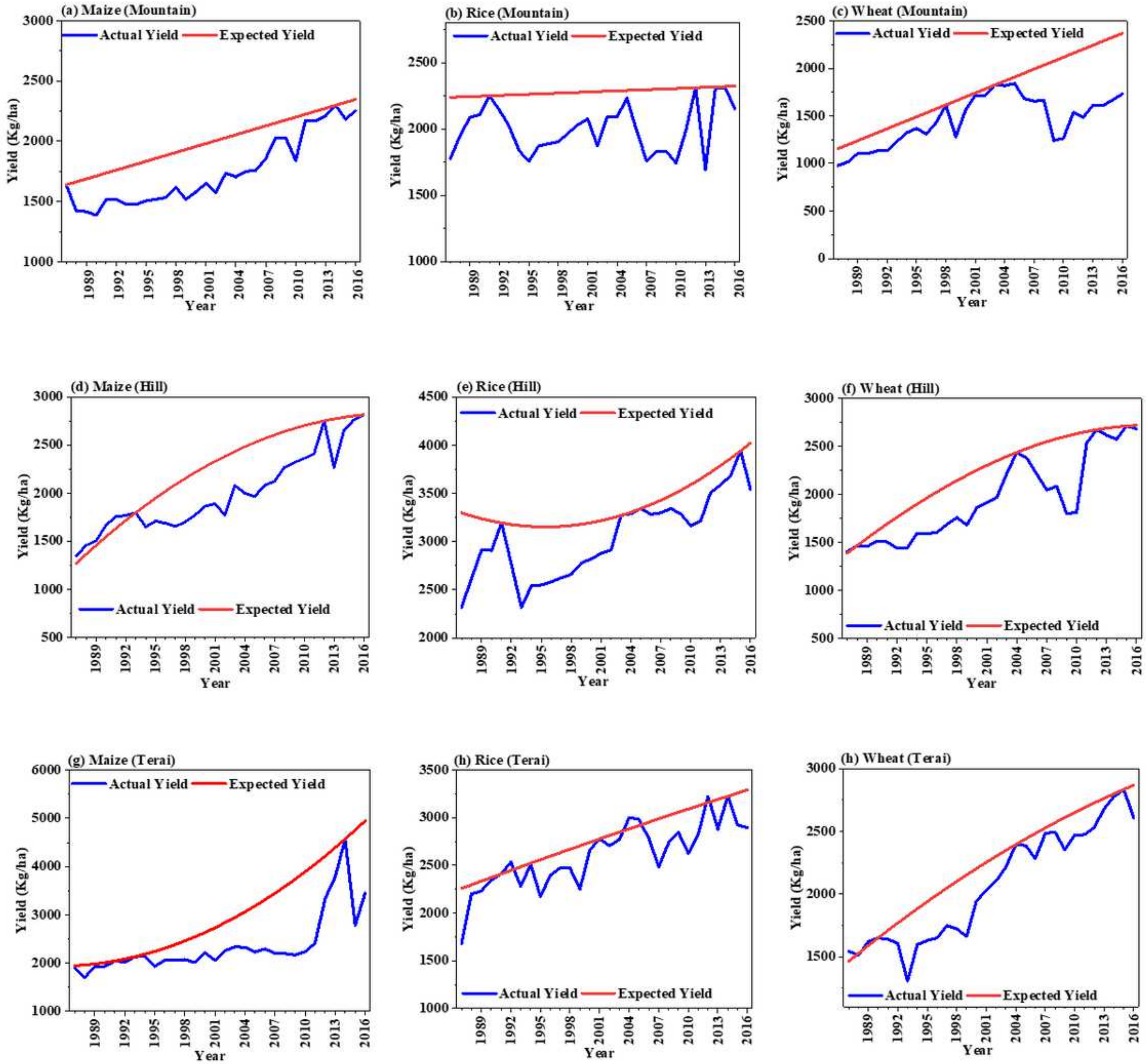

Figure 2

The actual and expected yield of maize, rice, and wheat yield from 1987 to 2016 in the mountain, hill and Terai regions of Koshi River Basin, Nepal.

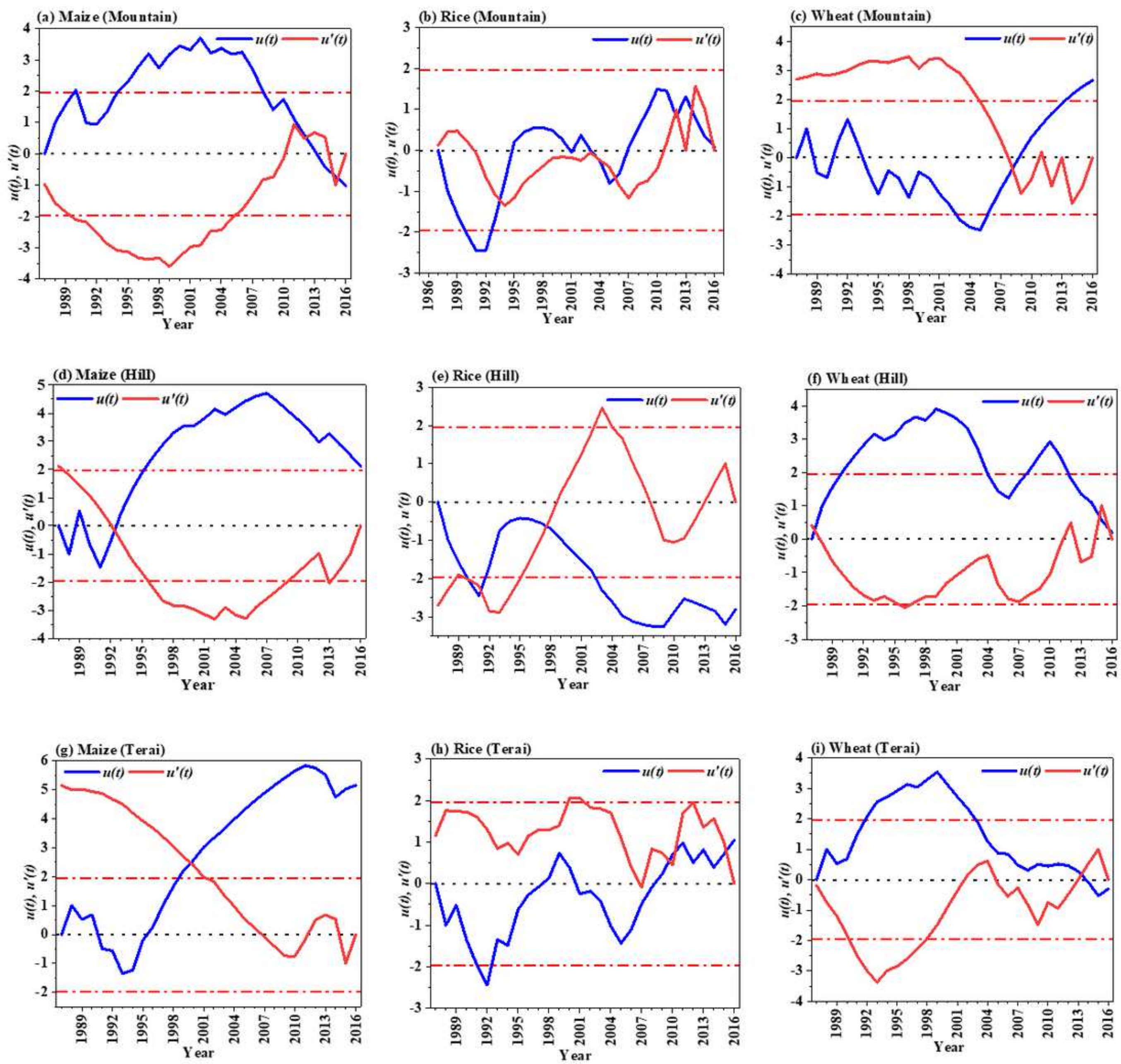

Figure 3

Graphical representation of the progressive series u(t) and retrograde series u'(t) of Sequential Mann-Kendall statistic test: (a-c) maize, rice and wheat yield loss in the mountain, (d-f) maize, rice and wheat yield loss in the hill and (g-i) maize, rice and wheat yield loss in the Terai regions of KRB, Nepal. The red dash lines are the upper and lower critical values (±1.96, P = 0.05), respectively.

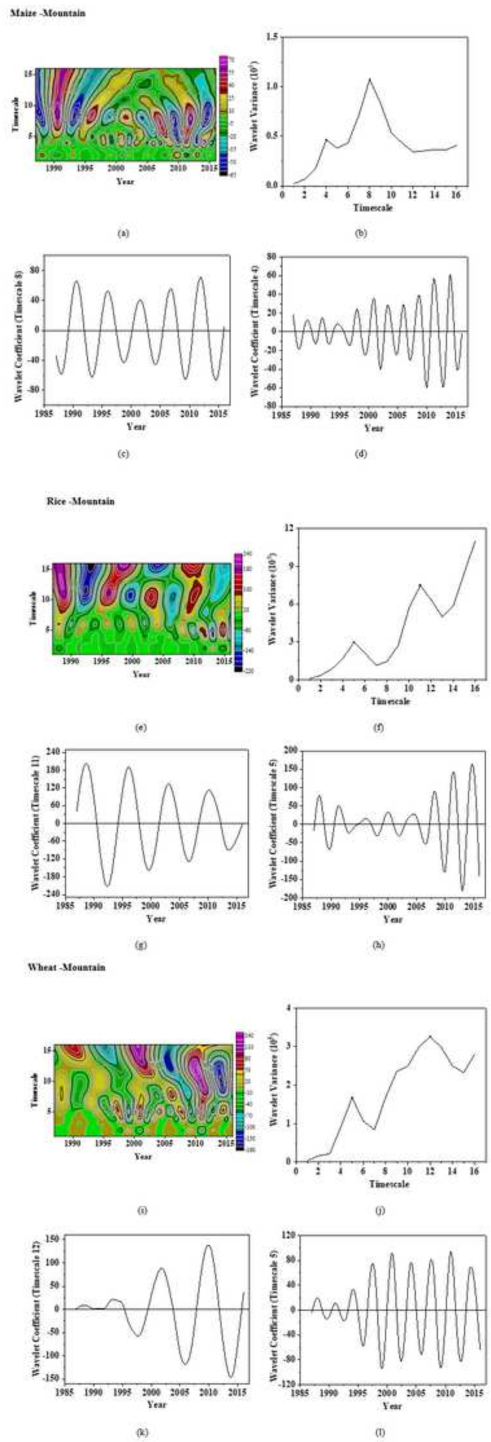

Figure 4

Wavelet coefficient contour map (a, e and i), wavelet variance diagram (b, f and j), major periodic oscillation at different timescale of maize, rice and wheat yield loss in the mountain region of the KRB, Nepal.

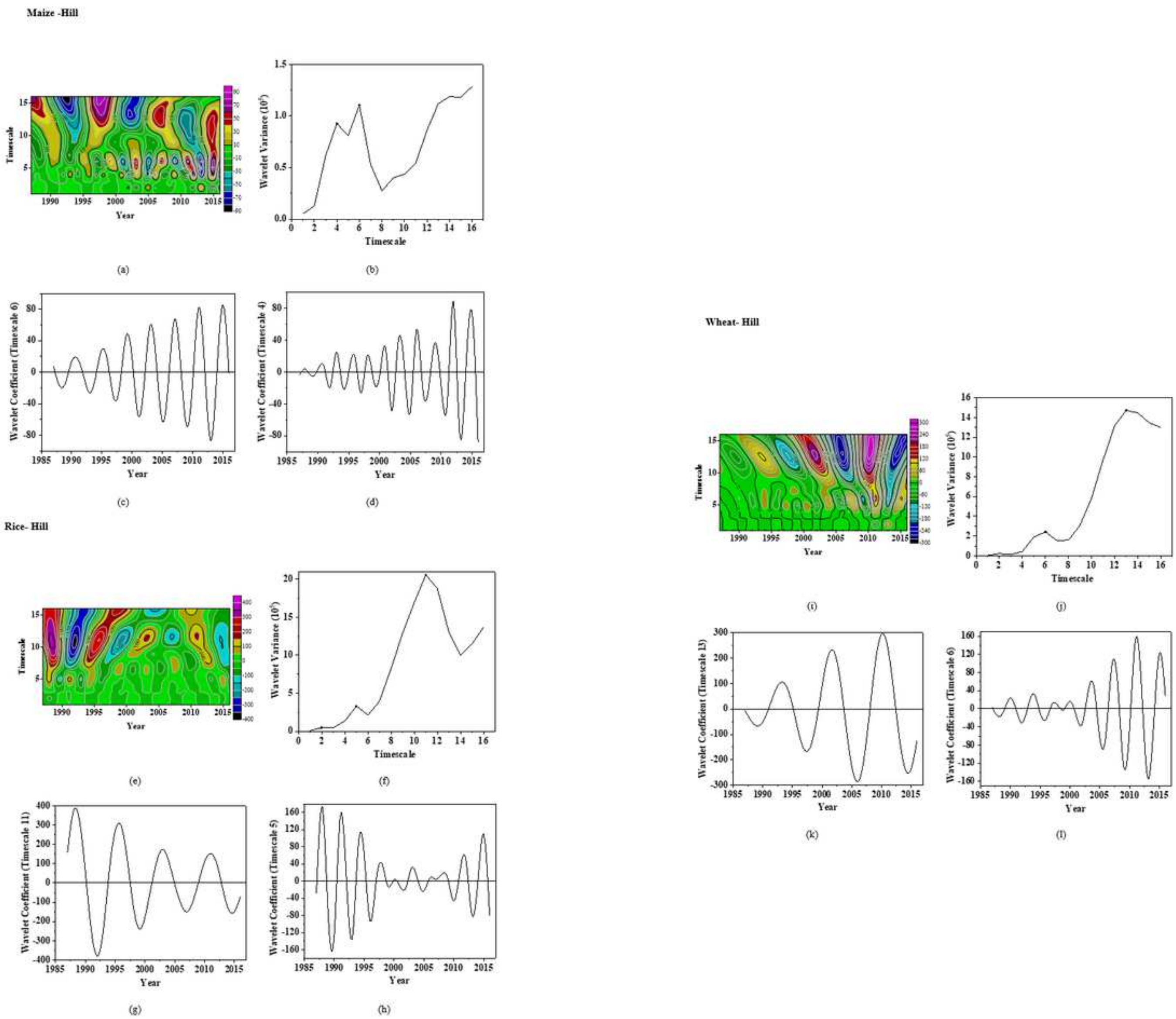

Figure 5

Wavelet coefficient contour map (a, e and i), wavelet variance diagram (b, f and j), major periodic oscillation at different timescale of maize, rice and wheat yield loss in the hill region of the KRB, Nepal.

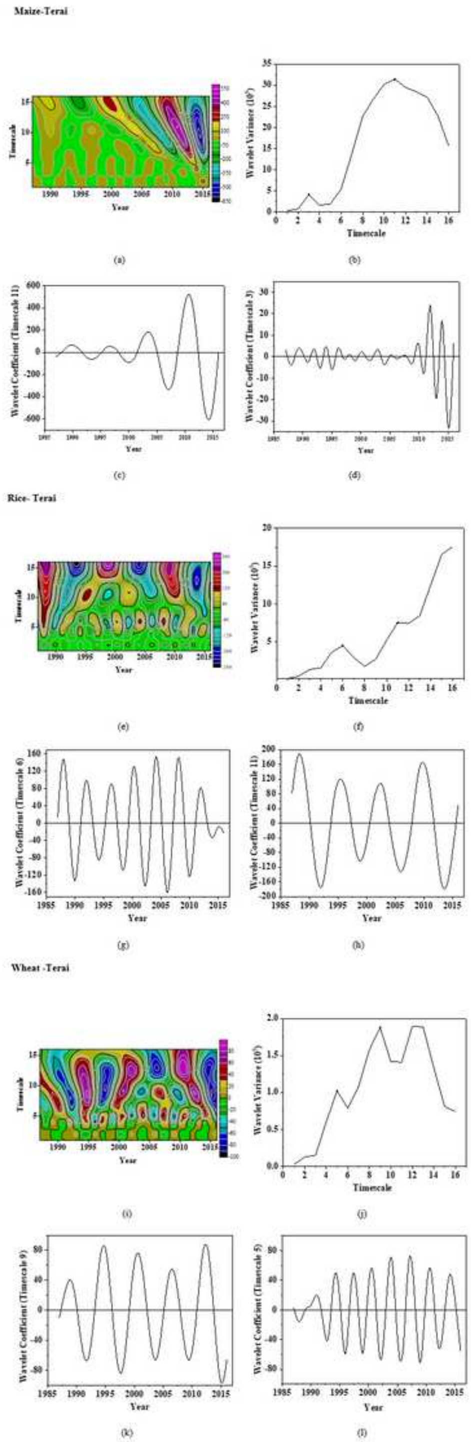

Figure 6

Wavelet coefficient contour map (a, e and i), wavelet variance diagram (b, f and j), major periodic oscillation at different timescale of maize, rice and wheat yield loss in the Terai region of the KRB, Nepal.