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ORIGINAL PAPER

El Nino/La Nina impact on crop production over different agro-climatic zones of Indo-Gangetic Plain of India

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Abstract
Estimates of fluctuation in climatic condition have a large impact on the production of selected crops such as rice (*Oryza sativa*), wheat (*Triticum aestivum*), maize (*Zea mays*), pulse, and sugarcane (*Saccharum officinarum*) which are the most prominent crops over Indo-Gangetic Plains (IGP). The influence of El Nino/La Nina on monsoon rainfall directly or indirectly affects the Indian crop over the Agro-Climatic Zones of Indo-Gangetic Plain (IGP). The detailed analysis has been carried out to show the impact of El Nino/La Nina and its association with crop production over sub-regions of IGP (lower, middle, upper, and trans IGP) during 1966–2009. During El Nino years, the production and yield of Rice and sugarcane have been affected in the middle and upper regions of IGP. The production of wheat decreased during La Nina events in the middle regions of IGP. The rice production has been severely affected by El Nino events over middle and upper IGP regions whereas wheat production increased. The decrease in maize production is observed in the upper and trans regions of IGP during El Nino. Pulse production decreased mainly in the middle, upper, and trans IGP during both events. The sugarcane production was highly affected during La Nina events overall sub-regions of IGP. The correlations among crop production, monsoon rainfall, and sea surface temperature (SST) anomaly of Nino 3.4 region during monsoon season are very insignificant during El Nino events. On other hand, La Nina event shows significant correlation over IGP. It has been noticed that on many occasions, deficit rainfall over IGP during summer monsoon season was responsible for decrease in crop production. Hence, alteration in Indian summer monsoon rainfall (ISMR) and sea surface temperature modulation of Nino 3.4 might have caused increase/decrease in the production of the crop.

1 Introduction

The crop production is influenced by environmental factors such as rainfall, temperature, humidity etc. It may act either synergistically or antagonistically with other factors in determining yields (Waggoner 1983). The increasing temperature and unpredictability in rainfall related to global climatic change may lead to serious direct and indirect consequences on crop production (Sinha and Swaminathan 1991). The El Nino Southern Oscillation (ENSO) causes the variation in atmospheric temperature, circulation, and rainfall amount along the tropics and subtropics. The ENSO impact is prominent over western Pacific Sea as drought and scanty rainfall affect Asia including India (Chattopadhyay and Bhatla 1993a, b, c, Chattopadhyay and Bhatla 2002), Indonesia, and Philippines. The drought/flood-like condition during El Nino/La Nina may also have impact on crop production over different climatic zones of India. The Indo-Gangetic Plain (IGP) region is most suitable for Indian crops because this region is rich in alluvium soil and there is plenty supply of water. Various studies were carried out before to describe the variation in ISMR over IGP (Sinha and Jain 1998; Adel 2002; Chowdhury and Ward 2004). The monsoon rainfall has large impact on total Kharif crop production due to fluctuation in rainfall over India (Parthasarathy et al. 1988; Gadgil 1996; Webster et al. 1998). As reviewed by Trenberth (1997), most of the El Nino events begin in the northern spring/summer and reach to the peak between November and January. A study by

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Bhatla et al. (2015) illustrates that ISMR variability is enhanced during the El Nino years and suppressed during the La Nina years. The significant negative precipitation anomalies over Indian landmass show that Monsoon activity increases considerably during La Nina years (Bhatla et al. 2006). Bhatla et al. (2016a, b) describe the association of drought/flood with El Nino/La Nina overall India and East Uttar Pradesh. The study of Selvaraju (2003) highlighted the significant inverse relationship of NINO3 SST anomalies and Indian food grain production and noticed that the rice crop production got severely affected during warm ENSO phase. Recent works on crop-climate relationship were studied over India along with the influence of monsoon rainfall and its potential predictors on major crop production (Kumar et al. 2004). A study by Zhang et al. (2008) observed a relationship between ENSO and rice yields in north and northwest China during 1960 to 2004 and noted that rice was vulnerable to El Nino events before 1980, while it seemed to be benefitted from the occurrence of such events after 1980. In a recent study, Bhatla et al. (2016a, b) describe the linkage of sea surface temperature over different Nino regions with ISMR over Indo-Gangetic plains.

India has many agro-ecological systems which show diversity in crops and cropping pattern. Kalra et al. (2014) explained the strategies to adapt in evaluating the climate change impact on agriculture. The rice-wheat cropping system is the most important predominant cropping system of the IGP in India (Koshal 2014). The demand for rice and wheat, the predominant staple foods, is estimated to increase to 122 and 103 million tons, respectively, by 2020 (Kumar 1998). A review of Gupta and Seth (2007) has presented the resource-conserving technologies of the rice–wheat cropping systems over the Indo-Gangetic Plains, and results show that the resource-conserving technology (e.g., conservation agriculture) improves yields, reduces the consumption of water, and reduces negative impacts on the environmental quality. Nagarajan (1998) and Rajaram (1999) describe in their studies that wheat crop has shown an increase in yield potential with time. The study by Gutierrez (2017) shows that La Nina has strong negative impact on wheat yield anomalies than El Nino and also emphasizes the importance of two ENSO extreme phases for the worldwide wheat market. Aggarwal et al. (2000) showed in their study that there is a high potential yield of rice–wheat systems in various districts/states of the IGP region but the potential is higher in the northwestern regions compared to the eastern region. Aggarwal and Mall (2002) explained that the direct impact of climate change on rice crops over different agro-climatic regions in India would always be positive irrespective of the various uncertainties. India is mainly known for *Kharif* and *Rabi* crops such as rice which is mostly grown in *Kharif* (June–October) season, while wheat is mostly grown in *Rabi* (December–April) season. The maize is mainly a rain-fed *Kharif* crop which is sown just before the onset of monsoon and is harvested after a retreat of the monsoon globally. Maize is known as a queen of cereals because it has the highest genetic yield potential among the cereals. The increase in temperature consistently decreases maize yields in the contemporary conditions (Chatterjee 1998). UMGP (upper middle Gangetic plains) which is the backbone of Indian agriculture contribute at least 20% cereal production of country and have experienced a gradual declining trend from 2000 onwards and the feature is dependable with increase in drought-affected area in UMGP from 20–25% to 50–60%, before and after 2000, respectively, and drought affected areas conform that at least 50% of the agricultural (cereal) losses is associated with drought. If this trend increases in the future, then India will face severe food shortages (Nath et al. 2017). Climate change is mostly associated with global warming, i.e., CO_2 concentration. Also, uncertain precipitation has an effect on Indian agriculture system (Aggarwal et al. 2000). Tripathi et al. (2014, 2016) studied the crop production yield using DSSAT model and statistical techniques. In most of the states of northwest India, Rabi food grain is highly influenced by temperature and the climate indices of Nino 3.4 SST regions, Southern Oscillation Index (SOI), Arctic Oscillation (AO), and North Atlantic Oscillation (NAO). Prediction of the result may be useful for increasing sustainable production through better agronomic practices over northwest India regions (Nageswararao et al. 2018).

The linkage of the Indian food grain production with El Nino, La Nina, and neutral years during 1966–2009 has been investigated in the present study. The main objective is to focus on impact of El Nino/La Nina on Indian food grain production, i.e., rice, wheat, maize, pulse, and sugarcane over different agro-climatic zones of Indo-Gangetic Plains. A detailed analysis of the association of food grain production with Indian summer monsoon rainfall and SST over Nino 3.4 region has been carried out.

2 Data and methodology

The study uses district-wise agriculture crop data (production) available from 1966 to 2009 for different crops (rice, wheat, maize, pulses, and sugarcane) over Indo-Gangetic Plains and its sub-regions during 1966–2009. Four different sub-regions of Indo-Gangetic Plain (IGP) were considered, namely, lower IGP, middle IGP, upper IGP, trans IGP (Fig. 1) and its detail is given in Table 1. The yearly agriculture data have been obtained from International Crops Research Institute in Semi-Arid Tropics (ICRISAT-IN). The El Nino conditions persist when the average 5-month running means of sea surface temperature (SST) anomalies in the Nino 3.4 area of the equatorial Eastern Pacific Ocean (5°N–5°S, 120°E–180°W) exceed 0.4 °C for 6 months or more. The Nino 3.4 SST index is based

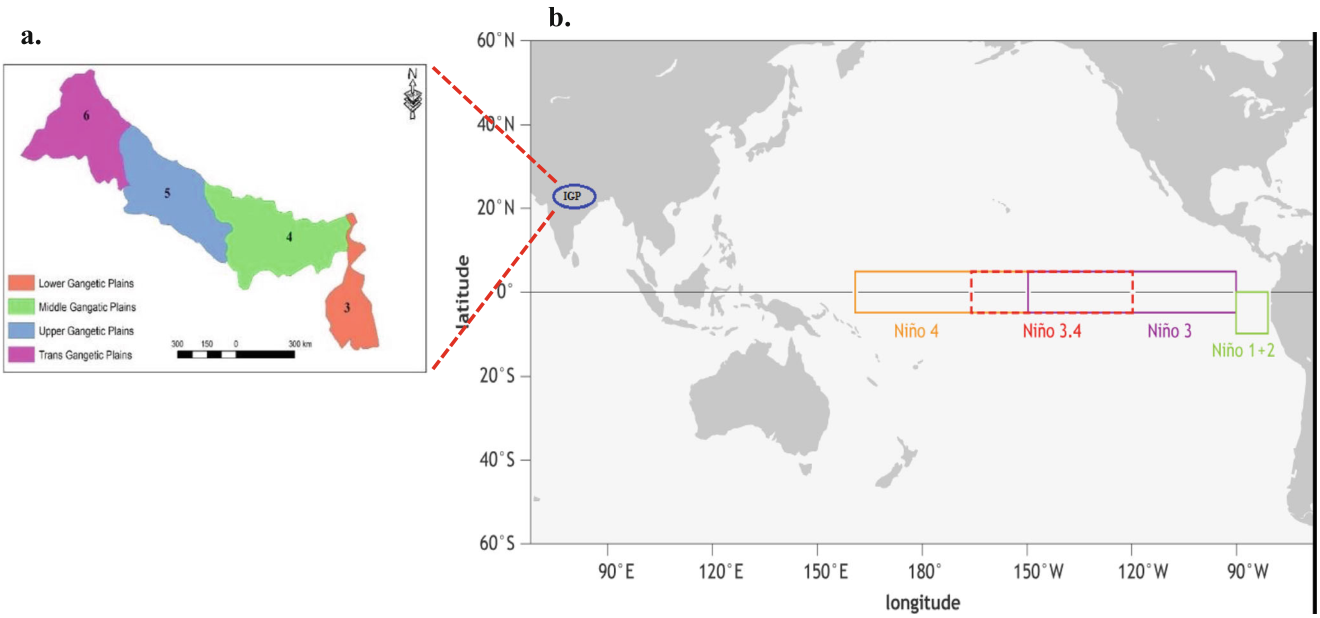

Fig. 1 **a**, **b** Geographical location of **a**. Indo-Gangetic Plain and its sub-regions (lower, middle, upper, and trans Gangetic Plains) in India on world map. **b** The dotted red color box is indicating Nino 3.4 SST regions of the tropical Pacific Ocean

on observed data for the period 1966 to 2009 and taken from NOAA, Climate Prediction Centre (www.cpc.noaa.gov). Out of total 44 years, 14 years are classified as El Nino and 12 years are classified as La Nina and the remaining 18 years as neutral years (Table 2). The rainfall data considered for the study over the different regions of IGP are taken from the website of Indian Institute of Tropical Meteorology, Pune (www.tropmet.res.in). Firstly, the contribution of major crop production over IGP region was analyzed; then, influence of monsoon rainfall and the climate indices of Nino 3.4 SST anomaly with crop production have been studied. The impact on crop production of the corresponding El Nino, La Nina, and neutral years has been analyzed using the percentage deviation in production of rice, wheat, maize, pulse and sugarcane over IGP region.

The percentage deviation in production from trend was calculated by

$$\text{Percentage deviation in production} = 100 \times \frac{(\text{Production}-\text{trend})}{\text{trend.}}$$

Table 1 The different regions of IGP and their stations

Regions of IGP	States	District
Lower-Gangetic Plains	West Bengal	24-Paraganas, Nadia, Murshidabad, Burdwan, Bankur, Birbhum, Hooghly, Howrah, Jalpaiguri, Darjeeling, Malda, Cooch-Behar, Purulia, Midnapore, West Dinajpur
Middle-Gangetic Plains	Bihar	Champaran, Muzaffarpur, Darbhanga, Saharsa, Purnea, Saran, Patna, Monghyr, Bhagalpur, SanthalParagana, Shahabad, Gaya
	Eastern Uttar Pradesh	Fatehpur, Allahabad, Banda, Varanasi, Mirzapur, Jaunpur, Ghazipur, Ballia, Deoria, Basti, Azamgarh, Lucknow, Unnao, Rae Barielly, Sitapur, Hardoi, Kheri, Faizabad, Gonda, Bahraich, Sultanpur, Pratapgarh, Barabanki, Gorakhpur
Upper-Gangetic Plains	Western and Central Uttar Pradesh	Saharanpur, Muzaffarnagar, Meerut, Bulandshahar, Aligarh, Mathura, Agra, Mainpuri, Etah, Bareilly, Buduan, Moradabad, Shahjahanpur, Pilibhit, Bijnor, Rampur, Farrukhabad, Etawah, Kanpur, Jalaun, Hamirpur
Trans-Gangetic Plains	Punjab, Haryana, Eastern Rajasthan	Gurdaspur, Amritsar, Kapurthala, Jalandhar, Hoshiarpur, Roopnagar, Ludhiana, Ferozpur, Bhatinda, Sangrur, Patiala, Hissar, Gurgaon, Jind, Mahendragarh, Ambala, Karnal, Rohtak, Alwar, Bharatpur, Churu, Ganganagar, Jaipur, Jhunjhunu, SawaiMadhopur, Sikar

Table 2 The list of El Nino, La Nina, and neutral year during 1966 to 2009

El Nino/rainfall average correlation/SST	La Nina/rainfall average correlation/SST	Neutral
1969	1970[b]	1966
1972[a]	1971[b]	1967
1977	1973	1968
1982[a]	1974	1976
1987[a]	1975[b]	1978
1991	1988[b]	1979
1992[a]	1996	1980
1993	1998	1981
1994	1999[b]	1983
1997	2000	1984
2002[a]	2007[b]	1985
2004[a]	2008[b]	1986
2006		1989
2009[a]		1990
		1995
		2001
		2003
		2005

[a] El Nino with drought year

[b] La Nina with flood year

The variability in crop production and trend analysis was illustrated by the percentage deviation of production for entire time series (1966–2009). It was calculated using the standard deviation and detrended each time series by taking the difference, $z_{\mathrm{i}} = z_{\mathrm{i}} - z_{\mathrm{i}-1}$ between the value z in each year i, and the value in the previous year $\mathrm{i} - 1$ (Box and Jenkins 1976). The correlation coefficient has been calculated during El Nino and La Nina events in between selected crops along with Nino 3.4 SST region for two consecutive months (JJA) and (JAS) months and monsoon rainfall (JJAS) over different sub-regions of IGP.

3 Results and discussion

3.1 Total crop production distribution and variation over IGP

The variability of crops viz. rice, wheat, maize, pulse, and sugarcane production over IGP and its different regions during the period of 1966–2009 is shown in Fig. 2. Figure 2 a shows the total production of crop in Indo-Gangetic Plain. It is well known that rice and wheat are the major food grains over IGP regions and wheat crop shows highest production over the region and the rice production shows a moderate increasing trend. IGP also contributes to production of pulse, maize, and sugarcane crops and the impact on production of crops may cause rise in temperature over India. Pulse crops are grown by farmers in less fertile soils and areas where less rainfall is received. Figure 2 b depicts the food grain variability for 1966–2009 over lower IGP which mainly includes West Bengal. Rice shows major contribution among all crops over lower IGP regions, and West Bengal's climate is suitable for rice crop production. However, other crops such as pulse, sugarcane, and maize show less production. On the other hand, wheat production increases in recent years (Fig. 2b). Hence, any change in climatic parameter may affect the quantity and quality of the crops. Figure 2 c indicates food grain variation period for 1966–2009 over middle IGP region. While there is decline in wheat production over middle IGP region, rice food grain shows the steady growth in production. Wheat and maize crops mainly depend upon rain fed in middle IGP. Other crops of middle regions of IGP such as maize and pulse do not show much contribution. It was observed that Uttar Pradesh is mainly contributing in the production of wheat and sugarcane crops and other crops such as maize and pulse show less production. Figure 2 d describes the regions consisting of the central and western part of Uttar Pradesh over upper IGP. Wheat and maize crops over upper region depend upon the rainfall in that particular region. Wheat shows increase in production but maize production was affected from other reasons such as use of fertilizers, selection of seed, and soil fertility. Figure 2 e shows that wheat and rice are the largest crop productions over trans IGP region as Punjab and Haryana are famous for wheat food grain production in Indian crops. It also shows low production of other

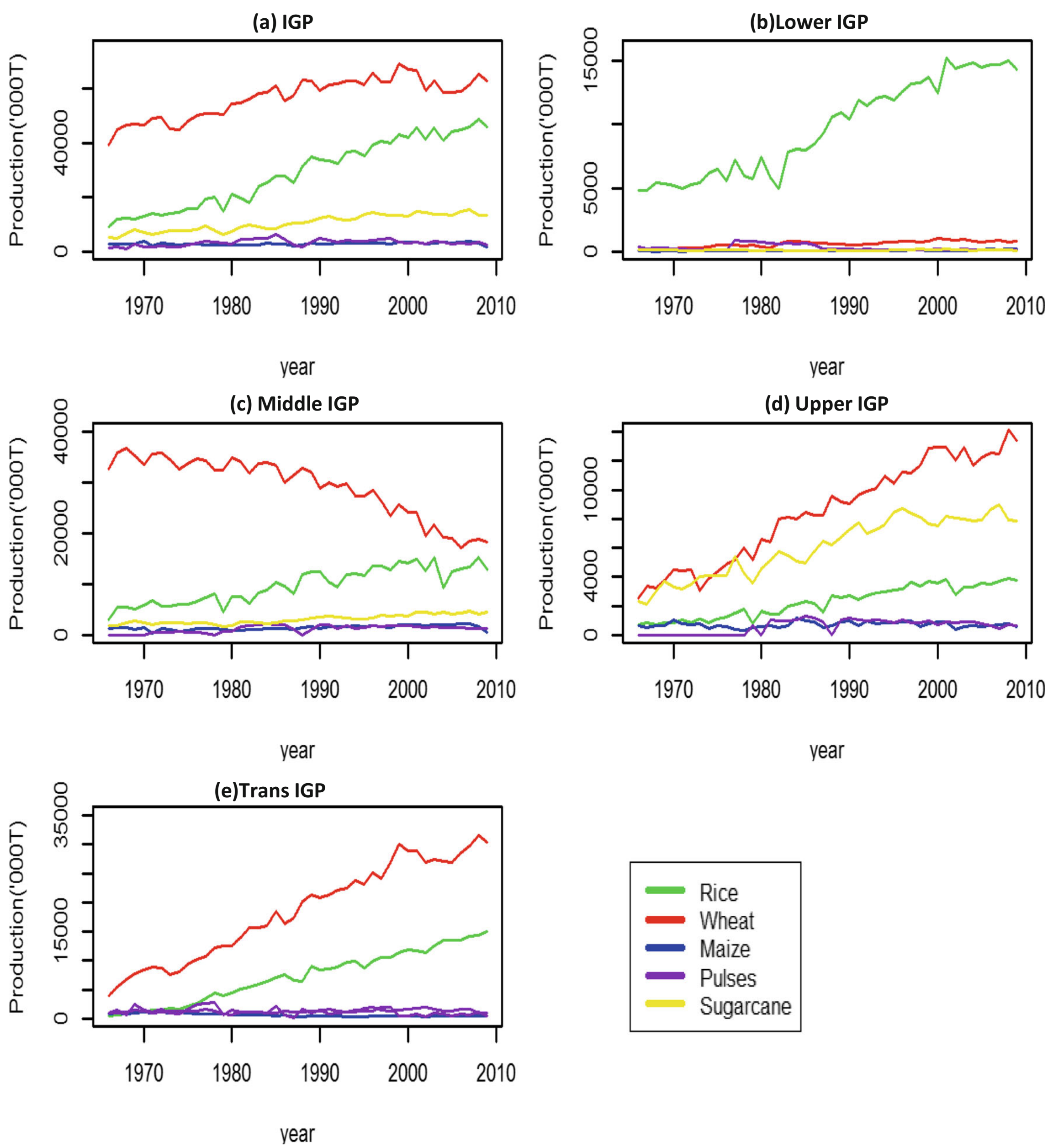

Fig. 2 **a**–**e** Total crop production variability of rice, wheat, maize, pulses, and sugarcane over Indo-Gangetic Plain and its sub-regions during 1966–2009. Where the average production in Million tonnes unit. **a** IGP, **b** lower IGP, **c** middle IGP, **d** upper IGP, **e** trans IGP

crops such as maize, pulse, and sugarcane over trans IGP region.

The percentage contribution of different crops over IGP and its various regions during period 1966–2009 are shown in Fig. 3a–e. Wheat and rice are highly produced crops and their percentage contributions are 55% and 28%, respectively. The other crops over IGP are sugarcane (11%), maize (3%), and pulse (3%) (Fig. 3a). Rice shows maximum contribution of 90% over lower IGP (Fig. 3b), 22% over middle IGP (Fig. 3c), 13% over upper IGP (Fig. 3d), and 25% over trans IGP region (Fig. 3e). These results show that after the green revolution, wheat and rice productions have increased significantly. Wheat is the major production in middle, upper, and trans IGP regions and it accounts for 65%, 47%, and 64% (Fig. 3 b, c, and e), respectively, whereas its contribution over lower IGP is only 5% (Fig. 3a). The maximum contribution of maize production is 4% over upper IGP region (shown in Fig. 3d). The contributions of maize production are 1% over lower IGP (Fig. 3b), 3% over middle IGP (Fig. 3c), and 2% over trans IGP (Fig. 3e). Trans region shows maximum production, i.e., 4% (Fig. 3e) of pulses among all regions of IGP, and contribution of other sub-regions of IGP is 3%. On other hand, sugarcane is grown as a commercial crop throughout India except for western Rajasthan, western Gujarat, and some

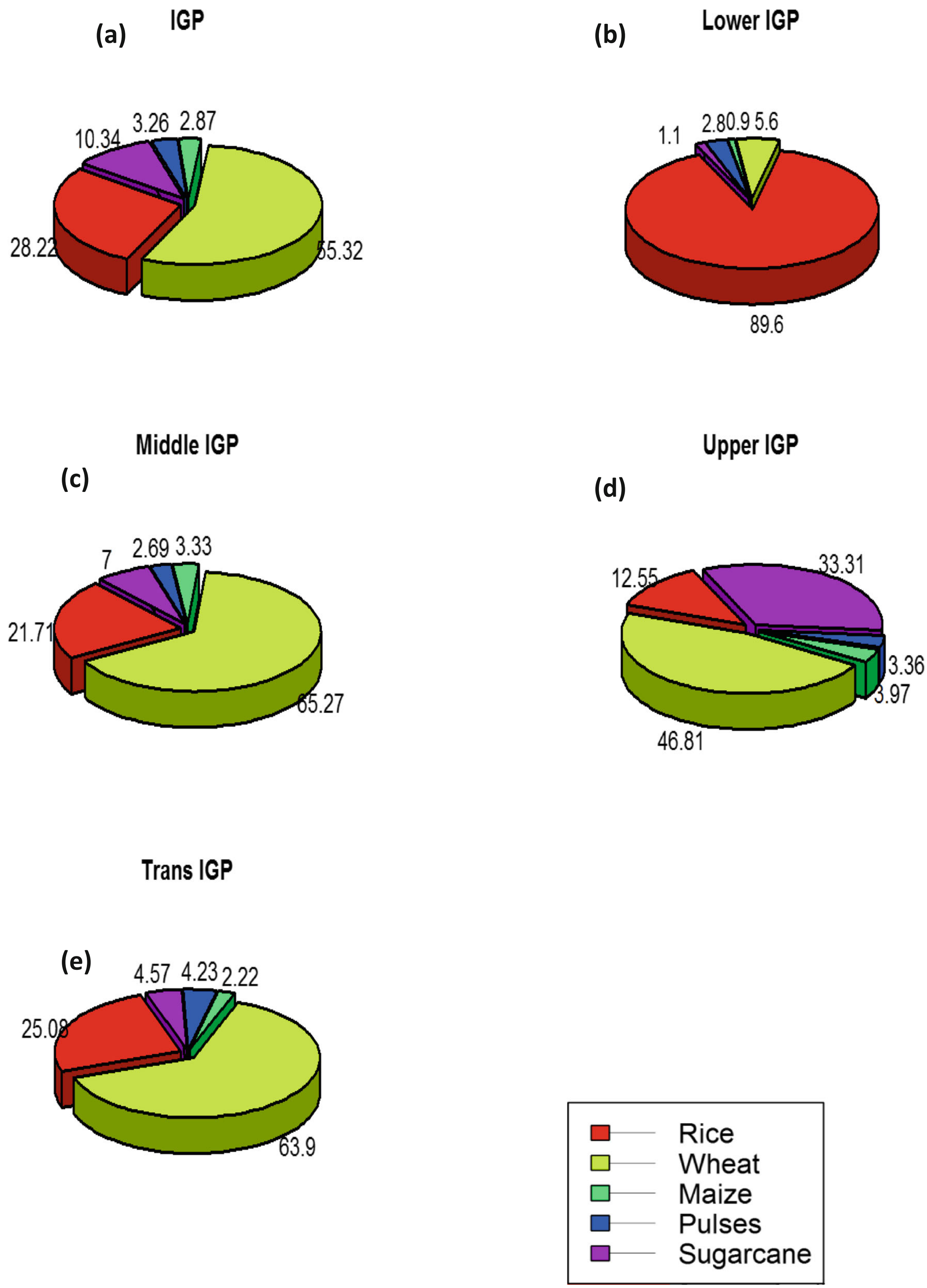

Fig. 3 **a**–**e** Percentage contribution of major crops: rice, wheat, maize, pulses, and sugarcane over different agroclimatic zones of Indo-Gangetic Plain during the period 1966–2009

Table 3 Correlation of crop production with monsoon rainfall and Nino 3.4 SST during El Nino events

Crops	Lower IGP			Middle IGP			Upper IGP			Trans IGP		
	Rainfall (JJAS)	SST (JJA)	SST (JAS)	Rainfall (JJAS)	SST (JJA)	SST (JAS)	Rainfall (JJAS)	SST (JJA)	SST (JAS)	Rainfall (JJAS)	SST (JJA)	SST (JAS)
Rice	0.36*	− 0.21	− 0.23	− 0.03	− 0.12	0.14	− 0.31	− 0.22	− 0.23	− 0.09	− 0.23	− 0.23
Wheat	0.26	0.02	0.02	0.28	0.27	0.22	0.53**	− 0.15	− 0.16	− 0.10	− 0.20	− 0.21
Maize	0.18	− 0.34*	− 0.34*	0.07	− 0.28	− 0.24	0.12	0.08	0.008	0.04	− 0.01	0.05
Pulse	− 0.23	− 0.09	− 0.06	− 0.07	0.07	0.03	− 0.44*	0.09	0.01	0.64***	− 0.11	− 0.06
Sugarcane	− 0.12	0.14	0.27	− 0.28	− 0.21	− 0.20	− 0.39*	− 0.12	− 0.13	0.04	− 0.09	− 0.09

*Significant at 2% level of significant

**Significant at 1% level of significant

***Significant at 0.5% level of significant

northeastern states. The contributions of sugarcane crop are 1% in lower IGP, 7% for middle IGP, 5% in trans IGP, and 33% over upper region which is highest among all sub-regions and is shown in Fig. 3 b, c, e, and d, respectively.

3.2 Correlation between crop production with rainfall/SST during El Nino and La Nina years over sub-regions of IGP

The rainfall over India during summer monsoon season (June to September) significantly influences the agricultural production. The correlations between ISMR (June to September) rainfall, SST over Nino 3.4 region during JJA and JAS, and food grain production over different regions of IGP during El Nino and La Nina years are shown in Table 3 and Table 4, respectively. Table 3 shows that during El Nino years, pulse crop has higher positive correlation ($r = 0.64$) significant at 0.5% level over trans IGP. Pulse crop shows negative correlation ($r = -0.44$) and sugarcane shows the normal correlation ($r = 0.39$) significant at 2% level over upper IGP. As lightly strong positive correlation has been obtained between wheat crop and summer monsoon rainfall ($r = 0.53$) which was significant at 1% level over upper IGP. The rice shows normal correlation ($r = 0.36$) with rainfall which was significant at 2% level over lower IGP. Thus, during El Nino events, major food grain mostly shows less or negative correlation, due to deficit monsoon rainfall. During El Nino years, SST over Nino 3.4 region during JJA and JAS months shows strongest inverse correlation with maize food grain ($r = -0.34$) which is significant at 2% level while maize production in other regions of IGP except lower IGP shows poor correlation with SST during El Nino period (Table 3).

Table 4 shows the correlation analysis between crops and JJAS rainfall, average SST over Nino 3.4 region during JJA and JAS months, and crop production over different regions of IGP during La Nina years. Pulse shows the strongest positive correlation ($r = 0.60$) with rainfall and rice crop production shows negative high correlation value ($r = -0.54$) significant at 0.5% and 1% levels, respectively, whereas wheat crop shows negative correlation ($r = -0.48$) with rainfall which is significant at 2% level over trans IGP regions. Rice and wheat over trans IGP show 0.44 and 0.39 correlations, respectively, with SST during JJA months which were significant at 2% level. Rice, wheat, pulse, and sugarcane crops showed normal

Table 4 Correlation of crop production with monsoon rainfall and Nino 3.4 SST during La Nina events

Crops	Lower IGP			Middle IGP			Upper IGP			Trans IGP		
	Rainfall (JJAS)	SST (JJA)	SST (JAS)	Rainfall (JJAS)	SST (JJA)	SST (JAS)	Rainfall (JJAS)	SST (JJA)	SST (JAS)	Rainfall (JJAS)	SST (JJA)	SST (JAS)
Rice	− 0.15	0.44*	0.30	0.34	0.33	0.27	0.47*	0.33	0.21	− 0.54**	0.44*	0.31
Wheat	− 0.13	0.18	0.16	− 0.48*	− 0.60***	− 0.40*	0.49*	0.38	0.2	− 0.48*	0.39*	0.26
Maize	0.03	0.60***	0.36	0.06	0.21	0.00	0.07	− 0.11	0.06	0.19	− 0.10	0.008
Pulse	0.28	− 0.33	− 0.28	0.25	0.31	0.35	0.45*	0.39*	0.38	0.60***	− 0.17	− 0.35
Sugarcane	− 0.19	0.65***	0.45*	0.33	0.51**	0.29	0.38*	− 0.40*	0.28	− 0.34	0.03	0.07

*Significant at 2% level of significant

**Significant at 1% level of significant

***Significant at 0.5% level of significant

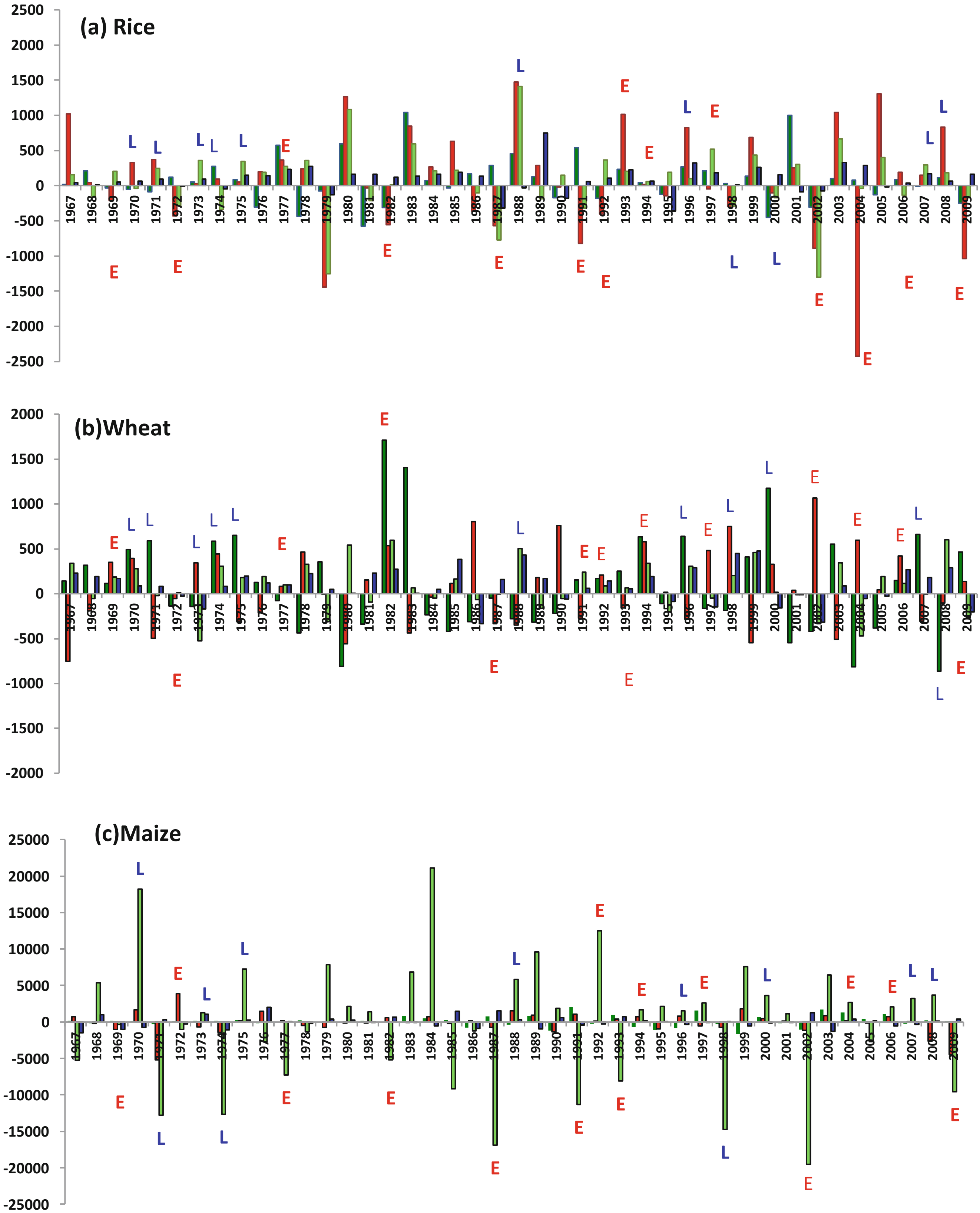

Fig. 4 **a**–**e** The time series bar plot is showing the impact of El Nino/La Nina on major crops: rice, wheat, maize, pulses, and sugarcane over crop production anomalies (1966–2009) in different agroclimatic zones of Indo-Gangetic Plains (IGP) during 1966–2009. Where El Nino and La Nina years denoted by 'E' and 'L', respectively

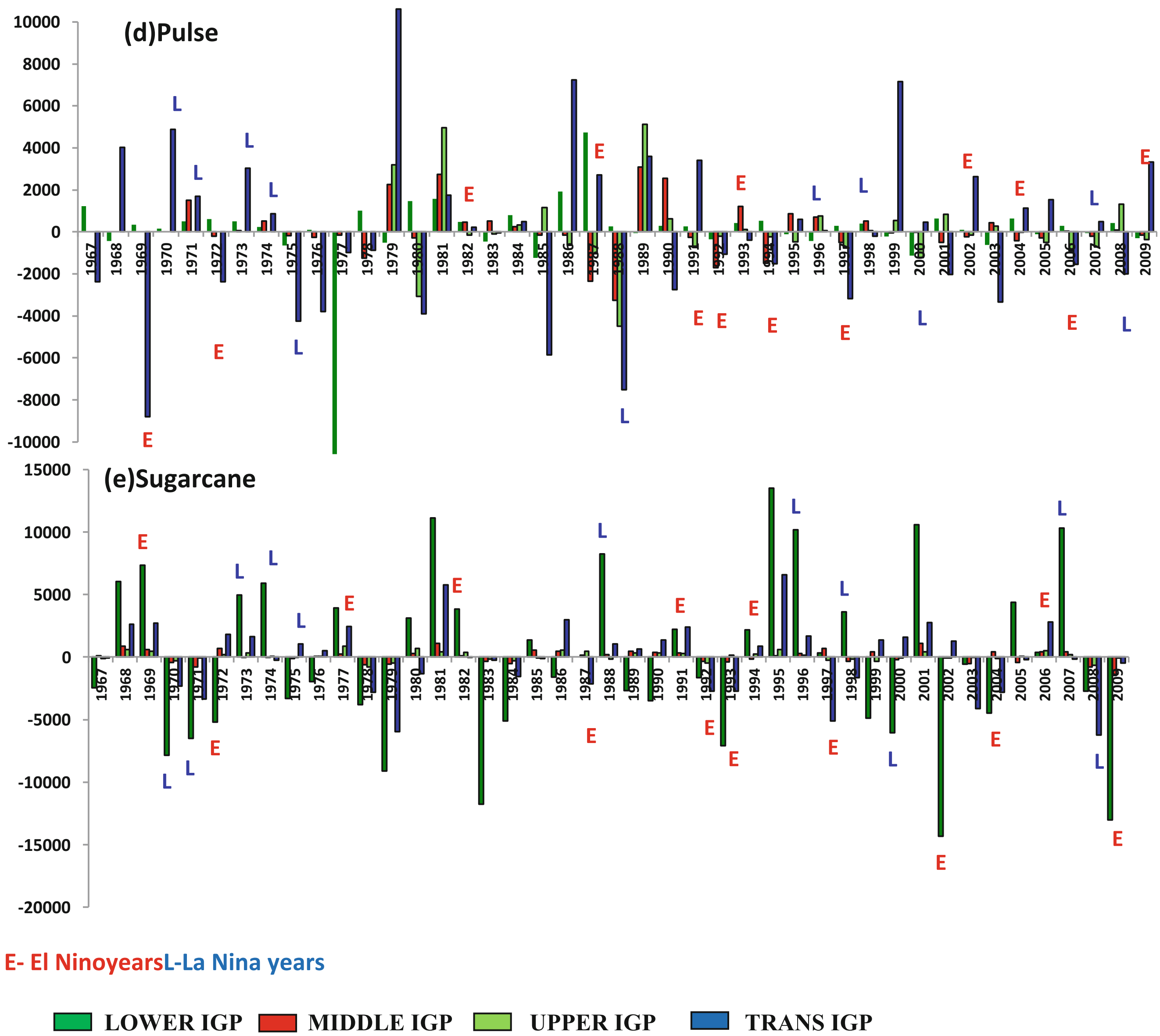

Fig. 4 (continued)

positive correlations of 0.47, 0.49, 0.45, and 0.38, respectively, with rainfall. Correlation of pulse crop with SST during JJA months was of 0.39 and sugarcane shows inverse correlation of − 0.40 which was significant at 2% level over upper region of IGP during La Nina events. Wheat food grain shows inverse correlation value of $r = -0.48$ with rainfall and was significant at 2% level and correlation of wheat crops with SST of JJA months shows negative correlation, i.e., $r = -0.60$ and sugarcane crop shows moderate positive correlation ($r = -0.51$) which were significant at 0.5% and 1% level, respectively (Table 4). While SST during JAS shows inverse correlation ($r = -0.40$) at 2% level significant over middle IGP regions during La Nina for wheat crops. Maize and sugarcane crops show strongest correlations, i.e., $r = 0.60$ and $r = 0.65$ with SST of JJA months and were significant at 0.5% level while sugarcane crop shows correlation of 0.45 with SST of JAS months which is significant at 2% level. Rice crop shows correlation of 0.44 at 2% significant level with SST of JJA months during La Nina events over lower IGP (Table 4).

3.3 Impact of crop production anomalies during El Nino, La Nina, and neutral years (1966–2009)

Impact of El Nino and La Nina on crop production anomalies studied over different sub-regions of Indo-Gangetic plain (lower, middle, upper and trans) shown in Fig. 4a–e during 1966–2009. Figure 4 a represents the percentage deviation of rice production over different regions (lower, middle, upper, and trans) of IGP during different ENSO phases, i.e., El Nino, La Nina, and neutral years. Throughout 44 years of period (1966 to 2009), 14 El Nino years, 12 La Nina years, and 18 neutral years were observed. Rice is dominant crop in lower IGP which shows 5 cases of negative deviations in its production during El Nino years, i.e., 1969, 1982, 1992, 2002, and 2009. El Nino is commonly associated with low rain or drought conditions such as1982, 1992, 2002, and 2009 which were drought years over India. During La Nina events, eight cases showed positive association of rice production, i.e., 1973, 1974, 1975, 1988, 1996, 1999, 2000, and 2008. Remaining 4 years (1970, 1971, 2000, and 2007) show decline in production due to surplus in monsoon rainfall. Ten neutral years also show positive values/increase in crop production and remaining 8 years show inverse relationship over lower IGP for rice production (Fig. 4a). Rice production in other regions such as middle IGP, upper IGP, and trans IGP shows decrease/increase in trend with the rate of − 5.059 mt/year, − 0.363 mt/year, and 0.974 mt/year, respectively, which are mentioned in Table 5. In middle IGP, 10 out of 14 El Nino years show the decrease in crop production in which most of the El Nino years were associated with drought condition and these are 1972, 1982, 1987, 1992, 2002, 2004, and 2009 during the period 1966–2009. The remaining four El Nino cases show positive association over middle IGP. During La Nina events, 10 out of 12 years are associated with positive values of crop production. The remaining 2 years show inverse relationship. This implies that the positive effect of La Nina on the production of rice in middle IGP (Fig. 4a). Among normal years, 13 out of 18 years show increase in crop production; on the other side, 5 years show inverse relationship of crop and ENSO over middle IGP. In the region of upper IGP, Central and Western Uttar Pradesh are considered for crop production as mentioned in Table 1, 8 events of El Nino are associated with decrease in crop production, and the rest of 6 events show positive effect in production. Eight out of 12 La Nina years show positive effect and remaining 4 years show inverse relationship as shown in Fig. 4a over Upper IGP region, while 13 neutral years show positive association and 5 years show inverse relationship. Figure 4 a depicts rice production association during the El Nino, La Nina, and neutral years during 1966–2009 over trans-IGP region. It is observed that out of 44 years of study period (1966–2009), 14 years show El Nino events. It was observed that 11 out of 14 years show positive values of association, 3-year El Nino shows the drought years, i.e., 1972, 1987, and 2002 shows the drop in rice production. Eight out of total 12 La Nina cases in considered period (1966–2009) show positive values of association and 4 years show inverse relationship. Rice production in 13 out of 18 neutral years show positive values of association and the relationship is inverse in remaining 5 years (Fig. 4a).

Table 5 The value of Sen's estimator of slope for rice, wheat, maize, pulses, and sugarcane production over Indo-Gangetic Plain and its sub-regions during 1966–2009 (average production in million tonnes unit)

Crops	Lower IGP	Middle IGP	Upper IGP	Trans IGP
Rice	− 0.352	− 5.059	− 0.363	0.974
Wheat	− 5.938	5.808	− 1.390	− 1.400
Maize	4.989	− 13.60	− 29.69	0.041
Pulse	5.713	− 14.05	− 31.30	16.30
Sugarcane	− 11.10	− 5.974	− 4.279	− 25.12

Impact of El Nino, La Nina, and neutral conditions upon production of wheat crops over sub-regions of Indo-Gangetic Plain (IGP) during the period 1966–2009 is illustrated in Fig. 4b. The wheat production decreases with the rate of − 0.352 mt/year with small variance from the mean value in lower IGP. Further, six cases (1972, 1977, 1987, 1997, 2002, and 2004) show negative response during El Nino phase having drought condition (1972, 1987, 2002, and 2004) in wheat production over lower IGP. During La Nina phase, 8 out of 12 years are positively associated with wheat crop production (8/12) and remaining 4 years show decrease in production of wheat in which 1988 and 2008 years were associated with flood years and may cause decline in production (Fig. 4b). Seven out of 18 neutral years over lower IGP show positive values of association with wheat production and remaining 11 years show inverse relationship. An increasing trend was found with the rate of 5.808 mt/year of wheat crop production over middle IGP. Ten out of 14 El Nino cases were positively associated, and the rest of 4 years was negatively associated with severe drought condition. Six out of 12 La Nina years are positively associated (6/12) and the rest of 6 years shows decrease in wheat production over middle IGP. The wheat crop production association during normal/neutral period is shown in Fig. 4b. It is observed that 8 out of 18 normal years show positive values of association with wheat production over middle IGP and 9 years show inverse relationship. The wheat production decreases over upper IGP region at a rate of − 1.39 mt/year with small variants from the mean value. Further, observation shows that 9 out of 14 years are positively associated (9/14) and 4 cases of El Nino years show inverse relationship with production and 1 year shows negligible production of wheat crop. Observation shows that only 4 out of 12 La Nina years have negative effect and the rest of 8 La Nina cases show positive production of wheat crop. During the normal/neutral crop production association, 9 out of 18 neutral years show positive values of association and remaining 9 years show negative relationship that may be due to changes in climate parameters. The variability of the wheat production series generally shows the decreasing trends at a rate of − 1.4 mt/year (Fig. 4b) over trans IGP region. Five years are negatively associated in total out of 14 El Nino years and remaining 9 cases of El Nino show positive production over trans IGP. Nine events out of total 12 La Nina years shows the positive production of wheat association (9/12) and 3 years are negatively associated (3/12) over trans IGP region. During the normal/neutral years, it is observed that 12 out of 18 neutral years show positive values of association, 6 years show inverse relationship in which 1 year shows negligible production of wheat crop as shown in Fig. 4b.

Effect of El Nino, La Nina, and neutral period on maize crops in sub regions of Indo-Gangetic Plain (IGP) for the study period of 1966–2009 is illustrated in Fig. 4c. Maize production increases at a rate of 4.99 mt/year with large variance from the mean value. It was found that 14 out of 44 years of study period show for maize crop production association over lower IGP during El Nino years. The 9 El Nino cases out of 14 El Nino events show increase in production while 4 years such as 1977, 1992, 1994, and 2002 are showing the very less in production due to severe drought over India. Further, observation shows that 7 out of 12 La Nina years are positively associated and 5 years show negative response due to flood and other climatic reasons for increase/decrease in crop production. Also, it is observed from Fig. 4c that 9 out of 18 normal years show positive values of association and the rest of the 9 years show inverse relationship. Nine out of 14 El Nino years are positively associated and the rest of 5 years are negatively associated and in which 4 years are extreme drought year (1987, 1992, 2002, and 2009) which show decline in maize production over middle IGP region. Four out of 12 La Nina years are positively associated and the rest of the 5 La Nina events with flood years such as 1975, 1983, 1971, 2007, and 2008 and show decrease in production of maize and the rest of 3 years show very less fluctuation in maize production. During the study period (1966–2009), 18 out of 44 years are neutral years. Eight out of 18 years show positive values of association with maize production and remaining 10 years show inverse relationship over middle IGP.

The maize production shows that there is decreasing trend with rate of 29.69 mt/year with large variance from the mean value in upper IGP region. It was found that 5 out of 14 years are positively associated in which some of El Nino years such as 1982, 1987, 2002, and 2009 were found to be drought years; on the other hand, the remaining 9 years are negatively associated. Eight out of 12 La Nina cases show positive maize production association while 4 cases are negatively associated over upper IGP. Out of 18 neutral years, 12 years have positive values of association with the maize production and the remaining 6 years show inverse relationship over upper IGP.

The maize production over trans IGP and its association during the El Nino, La Nina, and neutral years are shown in Fig. 4c. It increases at a rate of 0.041 mt/year with very small variance from the mean value. It was observed that 8 out of 14 years are positively associated (8/14) and 6 events of El Nino show negative association (6/14) over trans IGP region. Further, the observation shows that 6 out of 12 La Nina years are positively associated (6/12) and 6 years are negatively associated during La Nina years. Also, it was found that 7 out of 18 neutral years show positive values of association and 11 years show decrease in production (Fig. 4c).

Association of El Nino, La Nina, and neutral years with pulse crop production over different sub-regions of IGP is shown in Fig. 4d. During El Nino phase, 11 out of 14 events are positively associated (11/14); the rest of 3 events are negatively associated which may be due to extreme low rainfall condition. Pulse production increases with at a rate of 5.713 mt/years with large variance from the mean value in lower IGP. Further, the observation shows that 8 out of 12 La Nina years are positively associated (8/12) and the rest of 4 years are negatively associated. During neutral events, it was observed that 8 out of 18 years show positive values of association and remaining 10 years show inverse relationship in which 5 years were found to have negligible production over lower IGP.

Pulse production association over middle IGP shows decreasing trend of − 14.05 mt/year with large variance from the mean value during El Nino years. It was observed that 2 out of 14 El Nino years are positively associated. Generally, El Nino years associated with drought condition show severe decrease in pulse production and that is why 12 El Nino years are negatively associated in which 1 year does not have any production. Four out of 12 La Nina years are positively associated, 5 years are negatively associated, and 3 years show negligible production due to heavy rainfall (Fig. 4d). Eighteen out of 44 years of study period (1966–2009) show the neutral pulse production association over middle IGP. Also, it is observed that 8 out of 18 years show positive values of association, 7 years show inverse relationship, and 3 years show no production. Pulse was the only crop out of all crops considered that showed the opposite tendency during both El Nino and La Nina events and the production was reduced significantly.

It is found that only 1 out of 14 El Nino years is positively associated, 13 years are negatively associated in which 4 years has no production of pulse crop over upper IGP region, whereas only 2 cases of La Nina years are positively associated and the remaining 9 years are negatively associated in which 6 years show no production. Most of the La Nina years like 1970, 1971, 1975, 1988, and 2007 are associated with flood or heavy rainfall. Nine out of 18 neutral years show positive values of association, 5 years show inverse relationship, and the remaining 4 years show negligible change in the production.

Figure 4 d shows that the pulse production over trans IGP increases at the rate of 16.30 mt/year with a large variance from mean value during the El Nino years. It is found that 8 out of 14 El Nino years show the decrease in pulse production associated with El Nino years, i.e., 1972, 1982, and 1992 (drought years), and the remaining 6 years show the increase in pulse crop production over trans IGP. Further, observation shows that those 6 out of 12 La Nina years are positively associated with pulse crop production and the rest of 6 years have inverse relationship with pulse production. It was observed that 9 out of 18 neutral years show positive values of association and the remaining 9 years show inverse relationship (Fig. 4d).

Sugarcane crop production association over different subregions of IGP during 1966–2009 is shown in Fig. 4e. Production of sugarcane has decreasing rate of − 11.10 mt/year, − 5.974 mt/year, − 4.279 mt/year, and − 25.12 mt/year over sub-regions of lower IGP, middle IGP, upper IGP, and trans IGP, respectively, with large variance from the mean value. Seven out of 14 El Nino events are positively associated, whereas 7 years are negatively associated in which 1 year, i.e., 1987, shows no production and it was the El Nino year with extreme drought condition over lower IGP (Fig. 4e). The 6 years out of total 12 La Nina years are positively associated and the remaining 6 years show negative association due to flood during La Nina years. During neutral years, 7 out of 18 years show positive association with sugarcane production and 11 years show inverse relationship.

In middle IGP, it was found that 9 out of 14 El Nino years are positively associated and the rest of the 5 cases are negatively associated in which 2 years show drought years, and maybe, it is the reason behind low amount of production in the years 1992 and 2002. Four out of 12 La Nina years are positively associated and the rest of 8 years are negatively associated in which 4 years (1970, 1971, 1975, and 2008) are associated with flood years. These 4 years witnessed decrease in sugarcane production. It is observed that 12 out of 18 normal/neutral years show positive values of association and the remaining 6 years show negative association with the production of sugarcane. Over upper IGP, 9 out of 14 El Nino years are positively associated (9/14) and the rest of 5 years is negatively associated with sugarcane production. Out of 12 La Nina events, 4 are positively associated (4/12) and the rest of 8 are negatively associated. The crop production association is shown in Fig. 4e over upper IGP during the normal/neutral years. It is observed that 10 out of 18 neutral years show positive values of association and the remaining 8 years show inverse relationship with sugarcane production over upper IGP.

In trans IGP regions, 7 out of 14 El Nino events are positively associated and the rest of 7 years are negatively associated. The sugarcane food grain production association during the La Nina years over trans IGP is shown in Fig. 4e. Further, observations during La Nina years show that 6 out of 12 years are positively associated and the rest of 6 years are negatively associated in which 4 years (1970, 1971, 2007, and 2008) are severely flood-affected La Nina events. Figure 4 e also shows that 9 out of 18 years have positive values of association and the remaining 9 years show inverse relationship with sugarcane production over trans IGP regions.

4 Conclusions

The crop productions over all the sub-regions of IGP except lower IGP have been severely affected during ENSO phases of the period 1966–2009. The lower IGP region like West Bengal shows consistent responses during both El Nino and La Nina events. Rice crop productions in middle and upper IGP regions, i.e., Bihar and Uttar Pradesh states, are severely influenced by El Nino events and the production of wheat crop decreases during La Nina events in middle IGP. Excess/deficient summer monsoon rainfall also has a negative impact on the crop production over IGP. The productions of other selected crops such as maize over upper and trans subregions of IGP are also severely affected by El Nino conditions. Large changes in pulse crop production occurred during both events in all sub-region of IGP except lower IGP. The low production of a crop is primarily dependent upon the changed cultivars, fertilization, and agro-chemistry of region. Although changes in climate parameters like precipitation, CO_2, temperature, humidity, soil moisture, etc. also affect the crop production, so, it is necessary to identify the link of crop production variability with ISMR and its direct and indirect dependencies with teleconnected climatic modulator such as ENSO during a climatological period. Some of the reasons behind low production of crops may be associated with decrease in sugarcane production and its association with El Nino and La Nina events. The correlation analysis showing the sugarcane production is highly associated with La Nina events than El Nino events. Thus, the decreasing trend in the sugarcane production might be explained with the modulation of La Nina events over the IGP region. On the basis of past climate and crop relation, farmers can be motivated by the government to grow crops which are more resilient in the present and future climate. Several precautions may become beneficial for reducing the impact of El Nino on crops in drought years such as integration of small reservoirs with large reservoirs, watershed management, modern irrigation techniques, and improved seed varieties. Along with this, it is necessary to develop a risk assessment framework to identify the vulnerability and adaptation of IGP crop production to ENSO-related climate variability. This regional framework will be helpful in increasing sustainable production through better agronomic practices over the fertile region IGP.

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