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CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

Long-term yield variability and detection of site-specific climate-smart nutrient management practices for rice–wheat systems: an empirical approach

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SUMMARY

Identification of climate-smart nutrient management practices will overcome the ill effects of extreme climate variability on agricultural production under projected climate change scenarios. The rice–wheat cropping system is the major system used in India: using long-term yield data from Integrated Nutrient Management experiments on this system, the present study analysed trends in weather parameters and grain yield under different nutrient management practices. Twelve treatments with different combinations of inorganic (chemical fertilizer) and organic (farmyard manure (FYM), green manure (GM) and crop residue) sources of nutrients were compared with farmers' conventional practices. A significant increasing trend was noticed for rainfall during the rice season at Kalyani and Navsari, of the order of 137·7 and 154·2 mm/decade, respectively. The highest increase in maximum temperature was seen at Palampur (1·62 °C/decade) followed by Ludhiana (1·14 °C/decade). At all the sites except Ludhiana and Kanpur, the yield of the rice–wheat system showed an increasing trend ranging from 0·08 t/ha/year in Jabalpur to 0·011 t/ha/year in Navsari, under the recommended dose of inorganic fertilizer application. A significant decreasing trend of 0·055 t/ha was found in Ludhiana. For most of the sites, a combination of half the recommended dose of inorganic fertilizer and either FYM or GM to provide the remainder of the N required was sufficient to maintain productivity. The top three climate-resilient integrated nutrient management practices were identified for all the study sites. Thus, the present study highlights the adaptive capacity of different integrated nutrient management practices to rainfall and temperature extremes under rice–wheat cropping system in distinctive agro-ecological zones of India.

INTRODUCTION

The rice–wheat cropping system is the principal traditional agricultural production system in the Indo-Gangetic Plains of South Asia. It occupies *c.* 13·5 million ha spread over India, Bangladesh, Nepal and Pakistan (Ladha *et al.* 2000). In India, rice–wheat rotations cover *c.* 9·2 million ha (Jat *et al.* 2011) and they are the principal source of food and livelihood security for several hundred millions of people in this densely populated region (Paroda *et al.* 1994). It is estimated that by 2020, food grain requirement would be almost 30–50% more than the current demand (Paroda & Kumar 2000). Several researchers have studied the long-term rice–wheat experiments in South Asia and found that there are signs of stagnation or decline in yields, after an initial rise in productivity during the 1970s and early 1980s with the introduction of high-yielding varieties and adoption of improved cultural practices (ICAR 1998; Dawe *et al.* 2000; Duxbury *et al.* 2000; Yadav *et al.* 2000; Bhandari *et al.* 2002; Ladha *et al.* 2003; Pathak *et al.* 2003; Yadvinder-Singh *et al.* 2004; Nayak *et al.* 2012). Declining soil fertility, changes in water-table depth, deterioration in the quality of irrigation water and rising salinity, increasing resistance to many pesticides, and inadequate crop and nutrient management are considered as some of the general causes for this decline (Joshi & Tyagi 1994; Sinha *et al.* 1998; Ladha *et al.* 2003; Aggarwal *et al.* 2004). It is also reported

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that many of the systems have low yields because of inappropriate water management (Timsina & Connor 2001). The situation will be further complicated by climate change, which will have various direct and indirect influences on production.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007*b*) stated that the earth's temperature increased by 0·74 °C between 1906 and 2005, due to increases in anthropogenic emissions of greenhouse gases. In India, the mean annual temperature has shown a significant warming trend of 0·05 °C/decade during the period 1901–2003 and the period from 1971–2003 has seen accelerated warming of 0·22 °C/decade, with unprecedented warming during the last decade (Kothawale & Rupa Kumar 2005). Observational analysis of the data from121 weather stations spread over India has shown an increase in intensity and frequency of hot events and also a decrease in frequency of cold events (Revadekar *et al*. 2012). More than three quarters of the stations show decreasing trends in the number of cold events, and *c*. 0·70 stations show an increasing trend in hot events. It also reported that 11 of the last 12 years rank among the 12 warmest years in the globe since 1850 (IPCC 2007*a*). Several countries in the tropical Asia region have reported increasing surface temperature trends in recent decades (Rupa Kumar *et al*. 1994; NATCOM 2004; IPCC 2007*b*). The spatial patterns of observed extreme daily maximum temperatures indicate that the maximum temperatures recorded over the central parts of India exceed 45 °C, whereas along the west coast, the extreme maximum temperatures recorded range from 35 to 40 °C (NATCOM 2004). It has been estimated that for every 1 °C rise in mean temperature, there is a corresponding 7% decline in rice yield (Bouman *et al*. 2007). The International Food Policy Research Institute calculates a decline of 12–14% in world rice production by 2050 due to the effects of climate change (Nelson *et al*. 2009). Analysis of the historical trends of rice and wheat crops in the Indo-Gangetic Plains using regional statistics, long-term fertility experiments, conventional field experiments and crop simulation models has shown that rice yields during the last three decades are declining, which may be partly related to the gradual change in weather conditions (Aggarwal *et al*. 2000; Pathak *et al*. 2003). Wheat production could be reduced by 4–5 million tonnes with every 1 °C temperature throughout the growing period, even after considering positive carbon fertilization benefits but no other adaptation benefits (Aggarwal 2008). Several researchers have confirmed the decline in agricultural productivity with climate change through simulation approaches (Saseendran *et al*. 2000; Mall & Aggarwal 2002; Aggarwal *et al*. 2010; Subash & Ram Mohan 2012).

The Inter-Governmental Panel on Climate Change has projected that the global mean surface temperature will rise by 1·4–5·8 °C by 2100 (IPCC 2007*a*, *b*). Climate variability is also projected to increase, leading to uncertain onsets of monsoons and more frequent extremes of weather, such as more severe droughts and floods. In a recent study under the Coupled Model Inter-Comparison Project 5, projected under the business-as-usual scenario, mean warming in India is likely to be in the range of 1·7–2·0 °C by the 2030s and 3·3–4·8 °C by the 2080s relative to pre-industrial times, and precipitation may increase by 4–5% by the 2030s and 6–14% by the 2080s compared with the 1961–1990 baseline (Chaturvedi *et al*. 2012). An increase in the frequency of extreme precipitation days (> 40 mm/day) for 2060 and beyond is also predicted. In India, the monsoon enters over the main lands through the Kerala Coast during the last week of May to the first week of June, so rice can be transplanted in the puddled fields after good initial monsoon showers. Similarly, the monsoon starts to withdraw from the northwestern part of the country in the first week of September and has gone completely by mid-October. Hence, as far as the rice crop is concerned, June–October rainfall is crucial. Jearakongman *et al*. (1995) showed that grain yield was severely affected when standing water disappeared >20 days before anthesis, while the presence of standing water 20 days after anthesis resulted in higher yields. For wheat, the maximum temperature is more crucial than any other single climatic variable.

However, with the adoption of integrated nutrient management practices, the ill-effects of extreme climatic conditions can be minimized. There is an urgent need to quantify the response of different integrated nutrient management practices to extreme climatic conditions under the rice–wheat system under the projected climate-change scenario. The present study aims to: (i) understand observed trends in climate variables (ii) quantify the trends in the rice–wheat system productivity under various management practices (iii) investigate how the variability of rainfall and temperature affect productivity under different management practices and (iv) identify site-specific, climate-smart integrated nutrient management practices under the rice–wheat system.

Table 1. *Geographical coordinates, year of start, soil type, ecosystem type and agro-climatic regions/sub-region of the experimental sites*

Location	Year of start of experiment	Latitude	Longitude	Altitude (m asl)	Annual rainfall (mm)	Soil type	Ecosystem type	Agro-climatic regions/sub-region of planning
Ludhiana	1983	30°56′N	75°52′E	247	780·8	Typic-Ustochrepts	Semi-arid	Trans-Gangetic Plains/Plains
Kanpur	1983	26°	80°21′E	129	890·3	Udic -Ustochrepts	Semi-arid	Upper Gangetic Plains/South Western Plains
Jabalpur	1985	23°	79°57′E	411	1379·1	Chromusterts	Sub-humid	Central Plateau & Hills/Kymore Plateau and Satupura Hills
Palampur	1990	32°	76°03′E	1291	2206·4	Udic-Haplustalfs	Humid	Western Himalayan/High altitude Temperate
Faizabad	1984	26°47′N	82°12′E	113	912·3	Udic-Fluvents	Sub-humid	Middle Gangetic Plains/Eastern Plains
Sabour	1984	25°	87°07′E	43	1229·1	Eutrochrepts	Sub-humid	Middle Gangetic Plains /South Bihar Plains
Raipur	1988	21°16′N	81°36′E	185	1188·0	Ochraquals	Sub-humid	Eastern Plateau & Hills/Wainganga
Kalyani	1986	23°40′N	88°52′E	11	1425·8	Fluventic Eutrochrepts	Humid	Lower Gangetic Plains/Central Alluvial Plains
Navasari	1987	20°57′N	72°54′E	9	1593·0	Vertic Ustochrets	Coastal	Gujarat Plains and Hills/Southern Hills

MATERIALS AND METHODS

Study sites and experimental details

The present study was based on the yield data collected under the aegis of the All India Coordinated Project on Farming Systems Research of the Indian Council of Agricultural Research, located at nine sites representing different agro-ecological zones of India (Table 1 & Fig. 1). The ecosystems range from humid regions (Palampur & Kalyani) to a coastal one (Navasari). The grain yield datasets from long-term experiments on integrated nutrient management in rice–wheat cropping systems at these nine sites were used. There are 12 rice–wheat system treatments with different combinations of inorganic and organic sources of nutrient inputs (Table 2). In *kharif* rice (i.e. rice grown during the monsoon season), the full recommended levels of nitrogen (N), phosphorus (P) and potassium (K) were supplied through either inorganic fertilizers alone or in a range of different combinations with different organic N sources [e.g. farmyard manure (FYM), crop residue (CR; wheat straw/paddy straw) or green manure (GM; sesbania, a leguminous crop – *Sesbania sesban* (L) Merr.)], so that the full recommended N dose was made available to the crop. The nutrient concentrations of FYM varies according to the source, conditions and duration of storage, whereas that of CR varies with the time or method of incorporation. However, in the case of GM, it depends on the incorporation age of the sesbania. On average the N, P, K contents (g/kg on oven dry basis) in FYM ranges from 8–12 N, 2–4 P and 3·5–6·5 K; CR had 4–6 N, 0·5–1·5 P and 2–4 K; and GM had 18–24 N, 1–3 P and 15–21 K (Bhandari *et al*. 2002). During June and July, the land was ploughed, puddled and levelled. For green manuring, an appropriate amount of above-ground sesbania biomass was chopped into 5–10 cm pieces, uniformly spread into the plot following flooding of the field and incorporated into the soil with an offset disc harrow, while the soil was being puddled for transplantion of rice. Sesbania was incorporated into the soil 1 day before transplanting. However, FYM and CR were incorporated into the moist soil 2 weeks before transplanting of rice. Two or three rice seedlings (25–30 days old) were transplanted in the puddle soil at 20 × 15 cm spacing. The *rabi* wheat (i.e. grown during the drier winter season) received inorganic NPK at the recommended dose only, and received no organic fertilizer inputs. After the rice was harvested in October–November, the land was prepared by

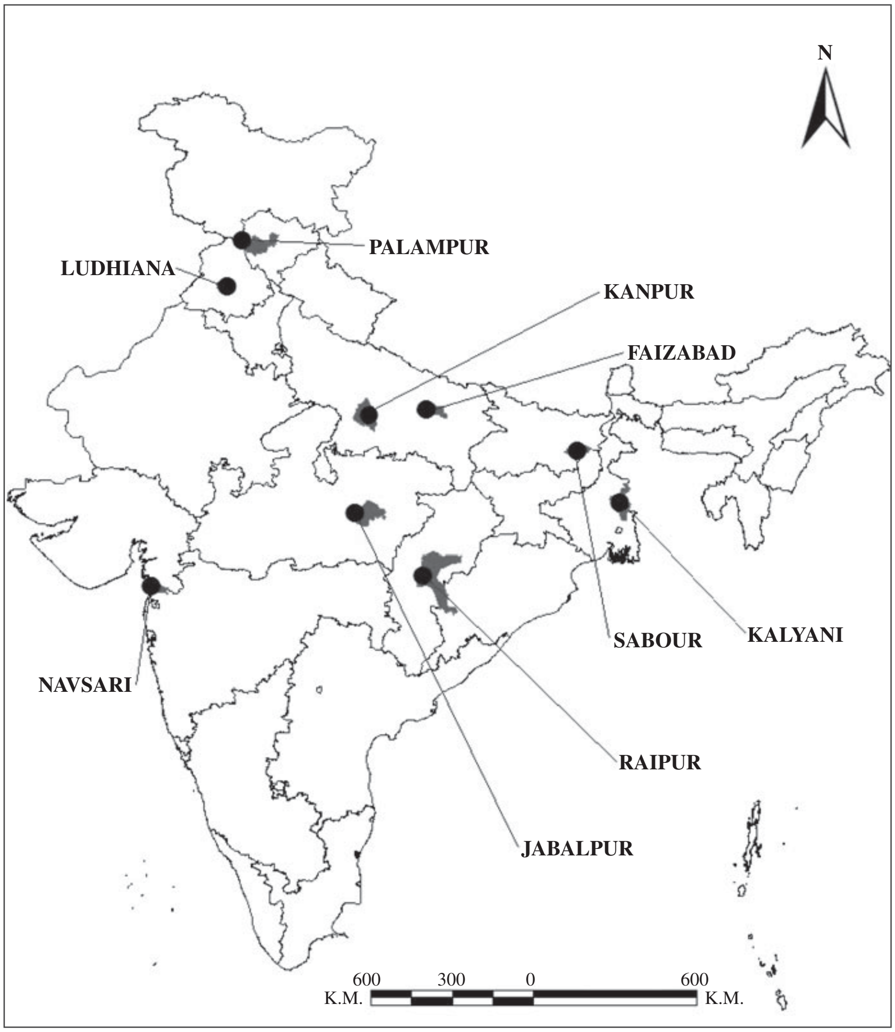

Fig. 1. Locations of the study sites.

ploughing and laddering, and wheat was sown. It was harvested in April. All P and K and half the dose of N were applied during sowing and the remaining N was top-dressed 21 days after sowing. Other recommended practices such as weeding, irrigation and plant protection measures were followed as per the recommended package of practices. During the long period of experimentation, the varieties were changed/replaced as per availability; however to continue the long-term nature of the experiment the varieties were selected in such a way as to match yields and duration to maintain the commonalities. Normally farmers were not followed the recommended dose of fertilizers and they apply different quantities and the 12th treatment dealt with farmers' practice and this also different for different sites. The site-specific experimental details are given in Table 3.

Weather data, trends and variability

Data were collected on the daily rainfall, maximum and minimum temperature and sunshine hours recorded at the nine study sites during the period 1980–2010. The observatories were installed many years ago under the guidance of technically qualified officers and the instruments calibrated according to the India Meteorological Department/World Meteorological Organization standard. All observations were recorded at the same time each day to maintain the homogeneity of readings. The Mann–Kendall (Mann 1945; Kendall 1975) non-parametric trend test, which uses the rank achieved by each entry in the data series, was used for trend analysis; it is a statistical yes/no-type hypothesis testing procedure for the existence of trends and does not estimate the slope of trends. The magnitude of the trends was estimated using Sen Slope

Table 2. *Experimental details*

Treatments	Rice	Wheat
T1	No fertilizer, no organic manure (control)	No fertilizer, no organic manure (control)
T2	0·50 NPK RDF	0·50 NPK RDF
T3	0·50 NPK RDF	1·00 NPK RDF
T4	0·75 NPK RDF	0·75 NPK RDF
T5	1·00 NPK RDF	1·00 NPK RDF
T6	0·50 NPK RDF + 0·50 N FYM	1·00 NPK RDF
T7	0·75 NPK RDF + 0·25 N FYM	0·75 NPK RDF
T8	0·50 NPK RDF + 0·50 N CR	1·00 NPK RDF
T9	0·75 NPK RDF + 0·25 N CR	0·75 NPK RDF
T10	0·50 NPK RDF + 0·50 N GM	1·00 NPK RDF
T11	0·75 NPK RDF + 0·25 N GM	0·75 NPK RDF
T12	Farmer's conventional practice	Farmer's conventional practice

RDF, recommended dose of fertilizer; FYM, farmyard manure; GM, green manure (sesbania, a leguminous crop – *Sesbania sesban* (L) Merr.); CR, crop residue (wheat straw).

Table 3. *Site-specific experimental details*

	Variety		Recommended dose of fertilizer (N–P_2O_5–K_2O, kg/ha)		Farmers' practice (N–P_2O_5–K_2O, kg/ha) + FYM	
Location	Rice	Wheat	Rice	Wheat	Rice	Wheat
Ludhiana	PR-116	PBW-343	120-30-30	120-60-30	120-30-30 + FYM	120-60-30 + FYM
Kanpur	P.Dhan-12	PBW-343	120-60-60	120-60-60	80-30-0	80-30-0
Jabalpur	Kranti	GW 273	160-60-40	120-60-40	40-20-0	40-20-0
Palampur	HPR-2143	HPW-184	90-40-40	120-90-30	36-16-16 + FYM	48-36-12 + FYM
Faizabad	Sarju 52	HUW 234	120-60-60	120-60-60	90-40-0	90-40-0
Sabour	Sita	PBW-343	80-20-40	100-50-25	60-30-15	68-33-0
Raipur	Mahamaya	GW 273	80-60-40	100-50-30	60-40-20	90-40-20
Kalyani	IET 4094	UP 262	80-40-40	100-60-40	50-30-20	60-20-20
Navasari	GR 3	GW 496	100-50-0	100-60-40	50-0-0 + FYM	60-30-0

FYM, farmyard manure.

(Sen 1968) and according to Hirsch *et al*. (1982), Sen's method was robust against extreme outliers. The Mann–Kendal test has been used by several researchers to detect trends in hydro-meteorological time-series data (Sneyers 1990; Serrano *et al*. 1999; Brunetti *et al*. 2000*a*, *b*; Kundzewicz & Robson 2000; Chiew & Sirivardena 2005; Subash & Ram Mohan 2011, 2012; Subash *et al*. 2011*a*, *b*). The averages of monthly, seasonal (rice season: June–October, wheat season: Novermber–April) and annual values for all weather variables and their SD and coefficients of variation (CV) (CV = (SD/mean) × 100) were calculated in order to find out the variability during the study period.

Yield trends

The parametric test was performed to determine the presence of linear trends by examining the relationship between time (experimentation period in years) and yield of rice, wheat and system productivity (*Y*) in terms of rice equivalent yield, using a least-squares linear regression:

$$Y = a + bt$$

where *Y* is the grain yield (t/ha) of rice or wheat or rice equivalent yield, *a* is the constant, *b* is the slope or magnitude of the yield trend (% change in yields per year) and t is the time (experimentation period in years). The rice equivalent yield was calculated according to the unit price of wheat and rice during the year 2012–2013.

Sustainability yield index

Several researchers (Reddy & Sudhakara Babu 2003; Sharma *et al.* 2005; Dinesh Kumar *et al.* 2009; Gui *et al.* 2010; Nayak *et al.* 2012; Srinivasarao *et al.* 2012*b*; Uzoho 2012) have used the Sustainable Yield Index (SYI) to determine the sustainability of different cropping systems under different integrated nutrient management practices in long-term fertilizer experiments. The SYI indicates the minimum guaranteed yield obtained under different treatments; higher SYI values indicate the treatments are less affected by seasonal variations. The SYI was suggested by Singh *et al.* (1990) and used to adjust any annual variations in the yield due to differences in rainfall and also to highlight the relative yield of the treatments for the long-term experimental study period. The SYI is defined as:

$$\mathrm{SYI} = (Y - \sigma)/Y_{max}$$

where Y is the average rice/wheat/system yield of a treatment/practice across the years, σ is the SD and Y_{max} is the observed maximum yield in the long-term experiment during years of cultivation. The SYI was calculated separately for rice, wheat and the rice–wheat system.

Detection of site-specific climate-smart nutrient management practices

Year-to-year yield variability in rice and wheat is driven largely by rainfall and maximum temperature, respectively. As mentioned earlier, several researchers have reported that the yields of rice, wheat and rice–wheat systems have been increasing, decreasing and stagnating, respectively, as far as long-term time-series data are concerned. Thus, to quantify the influence of climatic variables on yield, the yield must first be de-trended. The observed yields were de-trended in a conventional manner (McQuigg *et al.* 1973; Sakamoto 1978; Easterling *et al.* 1996; Gopinathan 2000; Challinor *et al.* 2003, 2005; Brown *et al.* 2008; Subash & Ram Mohan 2010, 2012) using a simple linear model with time as the independent predictor of yield. To normalize the yield, the yield anomaly index (YAI, the percentage deviation of the estimated trend yield to the actual yield) was worked out for rice, wheat and rice–wheat systems during the period of study for all the treatments.

The YAI for the *i*th year is

$$\mathrm{YAI_i} = (Y_i - \mathrm{TY_i}) \times 100/\mathrm{TY_i}$$

where $\mathrm{YAI_i}$ is the yield anomaly index for the *i*th year, Y_i is the actual yield for the *i*th year and $\mathrm{TY_i}$ is the technological trend yield for the *i*th year.

To quantify the influence of rainfall on rice yield, average YAI (for rice) was worked out for excess and deficit years based on half of the SD from the average seasonal rainfall during the crop season (mean ± 0·5 × SD) (seasonal rainfall ⩾ mean + 0·5 × SD for excess years, seasonal rainfall ⩽ mean–0·5 × SD for deficit years) for all the treatments. Similarly, to quantify the influence of maximum temperature on wheat yield, the average YAI (wheat) was worked out for years having an average maximum temperature during the wheat season ⩾ mean +1 °C for all the treatments. For the rice–wheat system, the simple average of rice yield anomaly and wheat yield anomaly indices (the rice–wheat (RW) anomaly index) was calculated for each treatment at all of the nine sites. The highest value of the RW anomaly index indicated the highest adaptive capacity of the treatment for sustainability under extreme climatic situations. Based on this index, the top three climate-smart nutrient management practices for rice–wheat systems were identified for each study site.

RESULTS

Rainfall variability and trends

The mean seasonal rainfall during the rice season varied from 615 mm at Ludhiana to 1718 mm at Palampur (Table 4) and the CV ranged from 25% at Sabour to 44% in Ludhiana. However, large-scale variability was seen in the distribution pattern (Table 5). July was the rainiest month in Ludhiana, Kanpur, Faizabad, Sabour, Kalyani and Navsari, but August was the rainiest month at Jabalpur, Palampur and Raipur. At all sites except Kalyani, the CV was >50% during June, indicating higher variability of rainfall during that month; this might be due to fluctuations in the date that the monsoon began as well as the overlapping of pre-monsoon showers with monsoon showers. It was also observed that the variability of rainfall is high (CV > 50%) for most of the month in the study sites. Even in September, the CV was >100%. In October, the CV for rainfall at all the

Table 4. *Seasonal mean, SD and coefficient of variation of weather variables during rice- and wheat-growing periods at the different study locations*

	Rainfall			Maximum temperature			Minimum temperature			Sunshine hours		
Location	Mean (mm)	SD (mm)	CV (%)	Mean (°C)	SD (°C)	CV (%)	Mean (°C)	SD (°C)	CV (%)	Mean (h/day)	SD (h/day)	CV (%)
Rice season (June–October)												
Ludhiana	615	269·2	44	34·2	0·58	2	23·7	0·49	2	8·3	0·82	10
Kanpur	820	294·0	36	34·0	0·83	2	24·6	0·73	3	DNA		
Jabalpur	1276	336·0	26	32·1	0·85	3	23·4	0·53	2	5·1	0·56	11
Palampur	1718	460·8	27	26·8	0·57	2	18·0	0·45	3	6·2	0·79	13
Faizabad	837	222·8	27	33·6	0·59	2	24·4	1·15	5	DNA		
Sabour	1064	260·8	25	32·6	0·50	2	24·8	0·37	1	DNA		
Raipur	1038	277·6	27	32·1	1·26	4	23·3	2·17	9	4·9	1·01	21
Kalyani	1124	321·2	29	33·1	0·70	2	25·4	0·40	2	5·5	0·35	6
Navsari	1577	478·0	30	30·9	1·28	4	24·5	1·37	6	DNA		
Wheat season (November–April)												
Ludhiana	145	87·0	60	24·6	0·88	4	10·3	0·65	6	7·9	0·65	8
Kanpur	54	43·3	80	27·6	0·82	3	12·4	0·84	7	DNA		
Jabalpur	94	75·6	80	29·6	0·64	2	12·9	0·69	5	8·2	0·32	4
Palampur	408	203·9	50	19·6	1·36	7	8·7	0·65	7	7·0	0·48	7
Faizabad	37	26·2	72	28·2	0·86	3	12·0	0·73	6	DNA		
Sabour	76–	51·8	68	27·8	1·48	5	13·3	0·52	4	DNA		
Raipur	89	46·4	52	31·8	1·39	4	15·5	1·65	11	8·2	1·32	16
Kalyani	172	107·1	62	30·3	0·81	3	16·8	0·50	3	8·2	0·39	5
Navsari	17	32·1	185	32·4	0·69	2	16·8	1·22	7	DNA		

DNA, Data not available.

Table 5. *Mean monthly rainfall (M)(mm), its SD and coefficient of variation (CV%) during the rice season at different study sites*

	Rainfall (mm)														
	June			July			August			September			October		
Location	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV
Ludhiana	63	52·6	83	232	156·4	67	192	129·2	67	115	152·4	133	13	25·3	197
Kanpur	74	64·1	87	272	179·8	66	251	142·7	57	180	119·3	66	43	72·8	170
Jabalpur	169	122·0	72	392	193·7	49	436	167·8	39	242	169·3	70	38	49·4	130
Palampur	222	128·3	58	579	251·5	43	652	180·3	28	233	120·9	52	32	43·8	136
Faizabad	116	89·5	77	255	138·7	54	243	112·7	46	181	94·7	52	42	46·0	111
Sabour	183	114·5	63	320	117·4	37	266	144·6	54	204	114·2	56	92	92·1	100
Raipur	189	148·7	79	293	164·2	56	295	134·3	46	184	134·2	73	53	45·4	86
Kalyani	228	110·2	48	278	123·3	44	250	92·2	37	255	127·7	50	115	96·7	84
Navsari	322	266·7	83	641	302·4	47	354	189·3	54	218	165·4	76	42	66·0	156

sites except Raipur and Kalyani, was >100%. Rainfall during the wheat season varied from 17·3 mm at Navsari to 407·5 mm at Palampur and CV at all the sites was >50%, ranging from 185% at Navsari to 50% at Palampur.

Positive trends were seen for rainfall during the rice season at all sites except Kanpur, Palampur and Faizabad, with significant increases of 137·7 ($P<0·05$) and 154·2 ($P<0·01$) mm/decade at Kalyani and Navsari, respectively (Table 6). However, decreasing trends were seen for rainfall during the wheat season at all sites except Sabour and Navsari (the latter showed no trend). Significant ($P<0·05$) decreases, of the order of 27·5 and 89·3 mm/decade, were recorded only at Ludhiana and Palampur, respectively, during the wheat season. As far as the monthly distribution of rainfall during the rice season is concerned, significant increasing trends for rainfall of the order of 50·7 mm/decade ($P<0·1$) and 31·8 mm/decade ($P<0·05$), respectively, were observed at Kalyani during September and October (Table 7). The trend for decreasing rainfall during August at most of the sites (seven out of nine) are a serious concern, as this period coincides with the tillering to flowering phase of the rice crop, which requires adequate moisture for potential growth.

Temperature variability and trends

The average seasonal maximum temperature during the rice season varied from 26·8 °C at Palampur to 34·2 °C at Ludhiana and the minimum temperature varied from 18·0 °C at Palampur to 25·4 °C at Kalyani. The minimum temperature was more variable compared with maximum temperature at Kanpur, Palampur, Navsari, Faizabad and Raipur. A trend for increasing maximum temperature was noticed at all sites except Ludhiana and Kalyani, but this was only significant at Kanpur and Palampur where increases of the order of 0·37 °C/decade ($P<0·05$) and 0·29 °C/decade ($P<0·05$), respectively, were observed. The average maximum temperature during the wheat season varied from 19·6 °C at Palampur to 32·4 °C at Navsari, while average minimum temperature varied from 8·7 °C at Palampur to 16·8 °C at Kalyani and Navsari. For most of the sites, higher variability in maximum and minimum temperatures was seen during the wheat season, as evident from the higher coefficient of variation values. With regard to temperature distribution during the wheat season, the lowest maximum temperature occurred in January at all the sites and varied from 15·2 °C at Palampur to 29·8 °C at Navsari (Table 8). The CV at Palampur is higher compared with all other sites for all the months. The trend in maximum temperature during March increased at all the sites except Kalyani, with the highest value of 1·62 °C/decade at Palampur followed by 1·14 °C/decade in Ludhiana. This is again of great concern since this period coincides with the grain filling stage of wheat at most of the sites, depending on the dates of sowing and varieties used. Statistically significant trends ($P<0·1$ to 0·01) for increasing temperatures were observed at four out of the nine locations (Ludhiana, Kanpur, Palampur and Faizabad). Significant trends for increasing temperatures during April, of the order of 0·73 ($P<0·01$) and

Table 6. *Trends (per decade) in seasonal rainfall, maximum and minimum temperature and sunshine hours during rice and wheat*

	Rice season				Wheat season			
		Temperature (°C/decade)				Temperature (°C/decade)		
Location	Rainfall (mm/decade)	Maximum	Minimum	Sunshine hours (h/decade)	Rainfall (mm/decade)	Maximum	Minimum	Sunshine hours (h/decade)
Ludhiana	+48·5	−0·12	+0·43 ($P<0·01$)	−0·7 ($P<0·01$)	−27·5 ($P<0.05$)	+0·48 ($P<0.05$)	+0·52 ($P<0·01$)	−0·5 ($P<0·01$)
Kanpur	−59·5	+0·37 ($P<0.05$)	−0·22	DNA	−7·1	+0·51 ($P<0·01$)	+0·07	DNA
Jabalpur	+25·9	+0·20	+0·01	+0·0	−6·9	+0·15	−0·02	−0·1 ($P<0.05$)
Palampur	−82·3	+0·29 ($P<0.05$)	−0·04	−0·4 ($P<0.05$)	−89·3 ($P<0.05$)	+1·12 ($P<0·01$)	+0·30 ($P<0·01$)	+0·2
Faizabad	−35·6	+0·05	+0·18	DNA	−4·7	+0·13	+0·10	DNA
Sabour	+40·7	+0·13	+0·08	DNA	+3·9	−0·04	+0·23 ($P<0·01$)	DNA
Raipur	+12·0	+0·14	+0·46 ($P<0·01$)	−0·1	−12·7	+0·26 ($P<0·1$)	+0·20	−0·30 ($P<0·01$)
Kalyani	+137·7 ($P<0·05$)	−0·10	−0·04	+0·30	−20·9	−0·04	+0·09	−0·40
Navsari	+154·2 ($P<0·1$)	+0·13	+0·90 ($P<0·01$)	DNA	0·0	+0·11	+1·20 ($P<0·01$)	DNA

DNA, Continuous sufficient data were not available for trend analysis.
Positive and negative values indicate increasing and decreasing trends, respectively, during the study period.

0·56 °C/decade ($P<0·1$) at Kanpur and Faizabad, respectively, are also of great concern, since the general practice of delaying the sowing date of wheat in these eastern parts of the Indo-Gangetic Plains extends the grain filling stage of the crop in April, adversely affecting grain size and therefore yield.

Sunshine variability and trends

The average sunshine hours during the rice season varied from 4·9 h/day in Raipur to 8·3 h/day in Ludhiana. However, during the wheat season, it varied from 7·0 h/day in Palampur to 8·2 h/day in Jabalpur, Raipur and Kalyani. The number of sunshine hours decreased during the rice season at all sites except Kalyani and significant decreases of the order of 0·7 h/decade ($P<0·01$) and 0·4 h/decade ($P<0·1$) were noted at Ludhiana and Palampur, respectively. Similarly, all the sites showed trends for decreasing sunshine hours during the wheat season, with significant trends for decreasing sunshine hours of the order of 0·5 ($P<0·01$), 0·3 ($P<0·01$) and 0·1 h/decade ($P<0·05$) observed at Ludhiana, Raipur and Jabalpur, respectively. For monthly trends, a decrease of sunshine hours was noted at Luhiana in all months except March, with significant ($P<0·01$) decreases of 0·9 h/decade during June and November and 0·6 h/decade during May (Table 9).

Long-term yield trends in rice–wheat yield

Rice yield trend

The time-series linear regression statistics of different treatments over the locations showed that no uniformity existed between the study sites (Table 10 & Figs 2(*a*) and (*b*)). It was noticed that at Ludhiana, all the treatments except farmers' practice showed decreased trends for rice yield ranging from 0·074 to 0·067 t/ha/year. However, the decreases seen for incorporation of FYM (to provide either 0·5 or 0·25 of total N) or GM (0·5 of total N) combined with inorganic source of nutrients were not significant. At Navsari and Kalyani, all treatments showed increasing trends. A significant ($P<0·01$) trend for increasing yield of the order of 0·071 t/ha/year was observed with incorporation of 0·25 N through FYM at Navsari. At Sabour, all treatments with application of the recommended dose of fertilizers either through inorganic sources or in combination with FYM, CR or GM showed highly significant ($P<0·01$) trends for increasing yield ranging

Table 7. *Trends (per decade) in monthly rainfall (mm/decade) during kharif (rice season) and maximum and minimum temperature (°C/decade) during rabi (wheat)*. P *levels are given in brackets*

Location	Rainfall (mm/decade)					Maximum temperature (°C/decade)						Minimum temperature (°C/decade)					
	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Nov	Dec	Jan	Feb	Mar	Apr
Ludhiana	+10·8 (<0·05)	−1·9	−4·1	+15·0	0·0	+0·46 (<0·05)	+0·03	−0·46	+0·30	+1·14 (<0·01)	+1·01 (<0·05)	+0·37 (<0·1)	+0·35	+0·17	+0·61 (<0·05)	+0·89 (<0·01)	+0·67 (<0·05)
Kanpur	+1·1	+5·0	−27·0	−29·1	−0·3	+0·43 (<0·1)	+0·39	+0·33	+0·46	+0·81 (<0·05)	+0·73 (<0·01)	−0·08	−0·31	−0·36	+0·25	+0·29	+0·26
Jabalpur	−17·8	+43·2	−20·7	+22·2	+2·7	+0·40 (<0·1)	+0·23	−0·18	+0·16	+0·28	+0·01	+0·35 (<0·05)	−0·06	−0·62	+0·12	+0·14	−0·12
Palampur	+3·5	−69·0	−26·5	+11·0	+2·7	+0·88 (<0·01)	+1·01 (<0·01)	+1·24 (<0·01)	+1·03 (<0·01)	+1·62 (<0·01)	+0·94 (<0·05)	−0·02	0·00	+0·28	+0·30	+0·68 (<0·05)	+0·46
Faizabad	−7·1	−12·9	−2·0	−16·8	+3·2	−0·15	−0·09	−0·45	−0·17	+0·64 (<0·1)	+0·56 (<0·1)	−0·06	−0·50	+0·16	+0·25	+0·41	+0·55
Sabour	+3·4	+12·5	+1·9	+6·4	−2·2	+0·07	−0·03	−0·39 (<0·05)	+0·27	+0·08	+0·04	+0·18	+0·35 (<0·05)	−0·05	+0·25	+0·42 (<0·01)	+0·16
Raipur	−6·9	+40·1	−33·5	+15·6	−0·4	+0·42 (<0·05)	+0·15	+0·28	+0·21	+0·12	−0·09	+0·81	+0·29	−0·38	+0·13	+0·41	+0·34
Kalyani	+31·6	+32·9	−1·3	+50·7 (<0·1)	+31·8 (<0·05)	+0·15	−0·06	−0·29	−0·09	−0·09	−0·17	+0·48	+0·09	−0·19	−0·17	+0·01	+0·24
Navsari	+29·0	+41·7	+56·4	+50·6	+0·0	−0·10	+0·08	−0·08	+0·02	+0·23	+0·06	+1·56 (<0·01)	+0·98 (<0·01)	+1·12 (<0·01)	+1·17 (<0·01)	+1·29 (<0·01)	1·04 (<0·01)

Positive and negative values indicate increasing and decreasing trends, respectively, during the study period.

Table 8. *Mean monthly maximum temperature (°C), its* SD *and coefficient of variation during the rice season at different study sites*

	Maximum temperature (°C)																	
	Nov			Dec			Jan			Feb			Mar			Apr		
Location	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV
Ludhiana	26·6	1·0	4	20·6	1·2	6	18·1	1·2	7	21·3	1·7	8	26·7	2·0	8	34·6	2·1	6
Kanpur	28·2	1·0	4	23·4	1·2	5	20·9	1·8	9	24·9	1·6	7	30·9	1·6	5	37·7	1·6	4
Jabalpur	28·8	0·9	3	25·6	1·1	4	24·5	1·1	5	27·6	1·4	5	32·9	1·7	5	38·4	1·2	3
Palampur	21·2	1·2	6	17·6	1·6	9	15·2	1·6	10	16·7	2·0	12	20·9	2·4	11	26·1	2·0	8
Faizabad	28·7	0·9	3	24·2	1·8	7	21·5	2·1	10	25·6	1·3	5	31·6	1·4	5	37·8	1·2	3
Sabour	28·4	0·7	2	24·1	1·0	4	21·8	2·3	10	25·5	2·2	9	31·2	2·6	8	35·9	2·9	8
Raipur	29·7	1·3	5	28·2	2·3	8	28·1	3·1	11	30·4	1·7	6	35·0	1·8	5	39·3	2·5	6
Kalyani	30·2	0·9	3	26·8	0·8	3	25·7	1·9	7	29·0	1·6	6	33·7	1·3	4	36·2	1·6	4
Navsari	32·8	1·8	6	30·9	1·1	4	29·8	2·1	7	31·6	1·4	4	34·1	2·0	6	35·2	0·9	2

from 0·084 tha/year with the addition of 0·5 N through GM to 0·026 t/ha/year with the application of inorganic fertilizer only. At Faizabad, all treatments except for the control showed increasing trends. This was highly significant ($P < 0·01$) for application of 0·5 N through FYM along with an inorganic fertilizer source of nutrients. In Jabalpur, all treatments except the control showed an increasing trend, with the highest value of 0·076 t/ha/year seen for application of 0·5 N through FYM treatment followed by 0·075 t/ha/year with the application of 0·5 N through CRs.

Wheat yield trend

In Ludhiana, all the treatments except 0·5 NPK (through inorganic fertilizers) showed an increasing trend in wheat yield, with significant ($P < 0·05$) increases of 0·029 and 0·028 t/ha/year for the application of 0·25 N through FYM and 0·25 through GM, respectively. All treatments except the control showed an increasing trend in Jabalpur, Kalyani and Sabour. Interestingly, all treatments with incorporation of FYM, CR or GM showed a significant ($P < 0·01$ to 0·1) increasing trend, with the highest (0·061 t/ha/year) noted with the application of GM. At Sabour, all treatments with application of the recommended dose of fertilizers either through inorganic fertilizers or in combination with FYM/CR/GM showed highly significant ($P < 0·01$) increasing trends ranging from 0·064 to 0·033 t/ha/year. At Pantnagar and Navsari, all the treatments showed trends for increasing yield. However, at Kanpur, trends for a yield decrease were seen for all treatments except for the three treatments with 0·5 of recommended inorganic fertilizer during both the rice and wheat season and 0·25 N through FYM and farmers' practice. The highest trend for decreasing yield of −0·026 t/ha/year was seen for the treatment providing 0·5 of the N through GM.

Rice–wheat system yield trend

All the treatments at Palampur, Kalyani and Navsari showed a trend for increasing yield of the rice–wheat system. The increase at Palampur ranged from 0·091 for farmers' practice to 0·023 t/ha/year for supply of 0·25 N through GM. However, at Navsari, a trend for greater increase of the order of 0·100 t/ha/year was seen with the incorporation of 0·5 N through FYM. At Sabour and Jabalpur, all treatments except the control showed trends for increasing yield: it was noted that all treatments with the recommended dose of fertilizer through either inorganic sources or in combination

Table 9. *Monthly trends (per decade) in sunshine hours (h/decade). P levels are given in brackets*

Location	Monthly trends in sunshine sunshine hours (h/decade)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ludhiana	−0·7 (<0·01)	−0·3 (<0·1)	+0·2	−0·2	−0·6 (<0·01)	−0·9 (<0·01)	−0·4	−0·4	−0·7 (<0·01)	−0·8 (<0·01)	−0·9 (<0·01)	−0·8 (<0·01)
Jabalpur	−0·1	0·0	−0·3 (<0·1)	0·0	−0·1	0·0	−0·1	+0·2	0·0	+0·1	−0·5 (<0·01)	−0·1
Palampur	+0·2	+0·2	+0·6 (<0·01)	0·0	−0·3	−0·5 (<0·1)	−0·3	−0·3	−0·5 (<0·05)	0·0	0·0	+0·4
Raipur	0·0	−0·1	−0·4 (<0·01)	−0·5 (<0·05)	−0·3	+0·2	−0·1	−0·1	−0·2	−0·3 (<0·1)	−0·4 (<0·05)	−0·3
Kalyani	−0·9	−0·3	−0·5	+0·2	−0·5	−0·2	+0·2	+0·6	+0·6 (<0·1)	−0·3	−0·4	−0·9 (<0·1)

Positive and negative values indicate increasing and decreasing trends, respectively, during the study period.

with FYM, CR or GM showed highly significant ($P<0·01$ to 0·1) trends for increasing yield at these locations. In Faizabad, trends for increasing yield were seen with application of the recommended dose of fertilizers either through inorganic sources or in combination with FYM/CR/GM along with the farmers' practice treatment. At Ludhiana and Kanpur, application of N through FYM treatments showed increasing yield trends while all other treatments showed decreasing yield trends. Application of the recommended dose of fertilizers through inorganic nutrient sources showed a trend for decreasing yield at both sites, with a significant ($P<0·05$) decrease of 0·055 t/ha/year in Ludhiana.

Changes in soil organic carbon, available nitrogen, phosphorus and potassium

The long-term application of FYM, CR and GM under various treatments on soil organic carbon, available N, P and K at 0–15 cm depth are shown in Tables 11 and 12. It is clearly seen that relative changes of soil organic carbon, available N, P and K compared with initial increased substantially in treatments with incorporation of FYM, CR and GM along with inorganic fertilizers compared with inorganic fertilizer alone treatments. However, the rate of increase will be different for incorporation of FYM, CR and GM as well as for different sites because of the differing soil types and textures and also due to different climates.

Changes in response of continuous application of nutrient management practices on yield

In order to determine the changes in response to continuous application of different nutrient management practices from the first to the last year of experimentation in the rice–wheat system over the control, the deviations between the average yields of the final 3 years (ending 2009) and those of the initial 3 years (ending 3 years after the start of the experiment) were calculated to avoid the effect of any particular year on yield response. It was noticed that for all the sites except Palampur and Navsari, the differences in yield deviation between the first and last 3 years showed positive values. This showed that the response of the crop to nutrient management either through inorganic fertilizers or in combination with FYM/CR/GM was higher compared with the control after 27 years of continuous rice cropping during the *kharif* season. However, the magnitude of response is different for different nutrient management practices

Table 10. *Long-term yield trend statistics under different fertilization treatments.* P *levels are given in brackets*

	Ludhiana						Kanpur						Jabalpur					
	Rice		Wheat		R–W system		Rice		Wheat		R–W system		Rice		Wheat		R–W system	
Treatments	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat
T1	−0·028 (<0·01)	−4·20	+0·011	+1·93	−0·016	−1·68	−0·026 (<0·05)	−2·12	−0·012 (<0·01)	−2·93	−0·039 (<0·01)	−2·68	−0·024	−1·29	−0·014 (<0·05)	−2·17	−0·038 (<0·05)	−1·94
T2	−0·057 (<0·01)	−4·79	+0·006	+0·52	−0·050 (<0·05)	−2·47	0·000	+0·02	+0·011	+1·18	+0·013	+0·78	+0·038 (<0·05)	+2·20	+0·035 (<0·01)	+2·59	+0·076 (<0·01)	+3·30
T3	−0·074 (<0·01)	−8·39	−0·030	−1·40	−0·107 (<0·01)	−4·12	+0·007	+0·63	−0·013	−1·23	−0·007	−0·47	+0·037 (<0·05)	+2·28	+0·009	+0·52	+0·047	+1·67
T4	−0·049 (<0·01)	−5·02	+0·012	+1·04	−0·035	−1·89	+0·002	+0·13	−0·009	−1·11	−0·007	−0·39	+0·017	+0·82	+0·024	+1·32	+0·043	+1·27
T5	−0·060 (<0·01)	−4·37	+0·005	+0·35	−0·055 (<0·05)	−2·42	+0·012	+0·71	−0·021 (<0·05)	−2·58	−0·011	−0·61	+0·044 (<0·05)	+2·50	+0·032	+1·85	+0·080 (<0·01)	+2·79
T6	−0·007	−0·52	+0·011	+0·80	+0·005	+0·19	+0·023 (<0·05)	+2·27	−0·019 (<0·05)	−2·35	+0·002	+0·18	+0·076 (<0·01)	+4·40	+0·048 (<0·01)	+2·88	+0·128 (<0·01)	+4·43
T7	−0·023	−1·26	+0·029 (<0·05)	+2·38	+0·009	+0·34	−0·004	−0·27	+0·010	+0·60	+0·007	+0·30	+0·029	+1·84	+0·042 (<0·05)	+2·53	+0·075 (<0·01)	+2·85
T8	−0·038 (<0·01)	−3·27	+0·013	+0·85	−0·024	−1·04	+0·021	+1·95	−0·023 (<0·05)	−2·49	−0·004	−0·28	+0·075 (<0·01)	+4·59	+0·037 (<0·05)	+1·95	+0·115 (<0·01)	+3·83
T9	−0·067 (<0·01)	−5·77	+0·021	+1·58	−0·044 (<0·05)	−2·02	+0·008	+0·65	−0·016	−1·76	−0·010	−0·66	+0·061 (<0·01)	+3·33	+0·054 (<0·01)	+3·67	+0·120 (<0·01)	+4·43
T10	−0·024	−1·47	+0·022	+1·42	0·000	+0·01	+0·016	+0·89	−0·026 (<0·01)	−3·00	−0·012	−0·59	+0·058 (<0·01)	+2·86	+0·061 (<0·01)	+3·67	+0·125 (<0·01)	+3·93
T11	−0·034 (<0·05)	−2·03	+0·028 (<0·05)	+2·36	−0·003	−0·14	0·000	0·00	−0·023 (<0·05)	−2·45	−0·025	−1·13	+0·023	+1·34	+0·047 (<0·01)	+2·77	+0·074 (<0·01)	+2·63
T12	+0·168 (<0·01)	+6·68	+0·183 (<0·01)	+7·39	+0·367 (<0·01)	+7·56	+0·003	+0·33	+0·001	+0·13	+0·004	+0·31	+0·045 (<0·01)	+2·73	+0·018	+1·38	+0·064 (<0·05)	+2·50
	Palampur						Faizabad						Sabour					
T1	+0·032 (<0·05)	+2·25	+0·036 (<0·01)	+3·31	+0·072 (<0·01)	+3·55	−0·012	−1·19	−0·020 (<0·01)	−2·91	−0·034 (<0·05)	−2·37	−0·028 (<0·01)	−9·32	−0·007 (<0·01)	−4·88	−0·036 (<0·01)	−9·74
T2	+0·013	+0·87	+0·026	+1·47	+0·041	+1·72	0·000	0·00	−0·014	−0·90	−0·015	−0·82	−0·008	−0·93	+0·008 (<0·05)	+1·99	0·000	+0·01
T3	+0·024	+1·28	+0·031	+1·24	+0·057	+1·75	−0·008	−0·68	−0·023	−1·52	−0·033	−1·76	−0·004	−0·48	+0·026 (<0·01)	+3·66	+0·024 (<0·05)	+2·21
T4	+0·017	+0·95	+0·027	+1·16	+0·046	+1·48	+0·004	+0·27	−0·024	−1·50	−0·022	−1·02	+0·008	+1·15	+0·008	+1·25	+0·018	+1·69
T5	+0·006	+0·32	+0·044 (<0·05)	+1·92	+0·054	+1·78	+0·033	+1·77	−0·007	−0·37	+0·026	+0·92	+0·026 (<0·01)	+3·32	+0·033 (<0·01)	+4·03	+0·062 (<0·01)	+4·69
T6	+0·035	+1·83	+0·038	+1·53	+0·076 (<0·05)	+2·38	+0·056 (<0·01)	+2·72	−0·005	−0·24	+0·051	+1·79	+0·079 (<0·01)	+8·25	+0·056 (<0·01)	+6·51	+0·140 (<0·01)	+8·62

Table 10. (*Cont.*)

Treatments	Ludhiana						Kanpur						Jabalpur					
	Rice		Wheat		R–W system		Rice		Wheat		R–W system		Rice		Wheat		R–W system	
	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat	B	*t*-stat
T7	+0·009	+0·48	+0·029	+1·51	+0·041	+1·62	+0·046	+2·52	−0·007	−0·47	+0·039	+1·58	+0·048 (<0·01)	+5·71	+0·057 (<0·01)	+6·59	+0·111 (<0·01)	+7·05
T8	+0·009	+0·56	+0·036	+1·47	+0·048	+1·73	+0·017	+0·92	0·000	+0·03	+0·018	+0·63	+0·079 (<0·01)	+8·04	+0·061 (<0·01)	+6·99	+0·145 (<0·01)	+8·43
T9	+0·004	+0·22	+0·022	+1·12	+0·028	+0·99	+0·032	+1·75	−0·018	−1·07	+0·012	+0·52	+0·055 (<0·01)	+5·61	+0·052 (<0·01)	+6·12	+0·112 (<0·01)	+7·21
T10	+0·013	+0·62	+0·043	+1·68	+0·059	+1·75	+0·050	+2·50	−0·011	−0·43	+0·039	+1·29	+0·084 (<0·01)	+8·49	+0·064 (<0·01)	+7·87	+0·153 (<0·01)	+9·20
T11	−0·001	−0·08	+0·023	+1·03	+0·023	+0·75	+0·050	+2·48	−0·010	−0·59	+0·040	+1·43	+0·058 (<0·01)	+6·44	+0·052 (<0·01)	+6·00	+0·115 (<0·01)	+7·16
T12	+0·040 (<0·01)	+2·69	+0·047 (<0·05)	+2·20	+0·091 (<0·01)	+3·07	+0·027	+1·89	+0·003	+0·20	+0·030	+1·32	+0·018 (<0·05)	+2·27	+0·046 (<0·01)	+6·20	+0·068 (<0·01)	+5·07
	Raipur						Kalyani						Navsari					
T1	−0·034 (<0·01)	−2·59	−0·032 (<0·01)	−3·36	+0·068 (<0·01)	−3·56	+0·011	+1·32	−0·008	−0·84	+0·003	+0·16	+0·044 (<0·05)	+2·13	+0·009	+0·61	+0·054 (<0·05)	+2·11
T2	+0·008	+0·36	−0·013	−0·64	+0·006	−0·20	+0·012	+1·02	+0·003	+0·17	+0·015	+0·57	+0·030	+1·17	+0·015	+0·67	+0·046	+1·57
T3	+0·028	+1·24	−0·031	−1·17	+0·006	−0·18	+0·034 (<0·05)	+2·44	+0·009	+0·62	+0·044	+1·76	+0·031	+1·62	+0·007	+0·29	+0·039	+1·39
T4	0·000	−0·02	−0·036	−1·31	−0·039	−1·02	+0·020	+1·45	−0·002	−0·15	+0·017	+0·66	+0·029	+1·14	+0·007	+0·29	+0·037	+1·17
T5	+0·032	+1·35	−0·018	−0·61	+0·013	+0·31	+0·026 (<0·05)	+2·09	+0·016	+1·09	+0·044	+1·86	+0·017	+0·69	−0·005	−0·20	+0·011	+0·33
T6	+0·014	+0·67	−0·034	−1·18	−0·024	−0·66	+0·048 (<0·01)	+3·41	+0·016	+1·03	+0·065 (<0·01)	+2·76	+0·057 (<0·01)	+3·08	+0·018	+0·61	+0·076 (<0·01)	2·53
T7	−0·007	−0·41	−0·049	−1·59	−0·060	−1·57	+0·030 (<0·05)	+1·99	+0·014	+0·87	+0·045	+1·63	+0·071 (<0·01)	+3·01	+0·027	+0·92	+0·100 (<0·05)	+2·87
T8	−0·006	−0·28	−0·029	−1·00	−0·037	−0·93	+0·042 (<0·01)	+2·91	+0·011	+0·62	+0·053 (<0·05)	+1·97	+0·016	+0·75	+0·023	+0·82	+0·040	+1·22
T9	+0·011	+0·52	−0·048	−1·56	−0·040	−0·98	+0·036 (<0·05)	+2·14	+0·028	+1·73	+0·067 (<0·05)	+2·24	+0·040 (<0·05)	+1·83	+0·032	+1·21	+0·075 (<0·01)	+2·48
T10	+0·016	+0·76	−0·031	−0·97	−0·018	−0·40	+0·021	+1·40	+0·024	+1·34	+0·047	+1·76	+0·026	+0·99	+0·020	+0·69	+0·048	+1·29
T11	+0·005	+0·25	−0·046	−1·40	−0·045	−1·10	+0·030	+1·74	+0·041 (<0·05)	+2·18	+0·074 (<0·05)	+2·42	+0·048 (<0·05)	+2·38	+0·021	+0·74	+0·071 (<0·05)	+2·02
T12	−0·032	−1·71	−0·049 (<0·05)	−1·80	−0·085 (<0·05)	−2·10	+0·052 (<0·01)	+3·38	+0·037 (<0·05)	+2·43	+0·092 (<0·01)	+3·62	+0·067 (<0·05)	+2·45	+0·005	+0·22	+0·073 (<0·01)	+2·46

B, Slope in t/ha (per year increase/decrease).

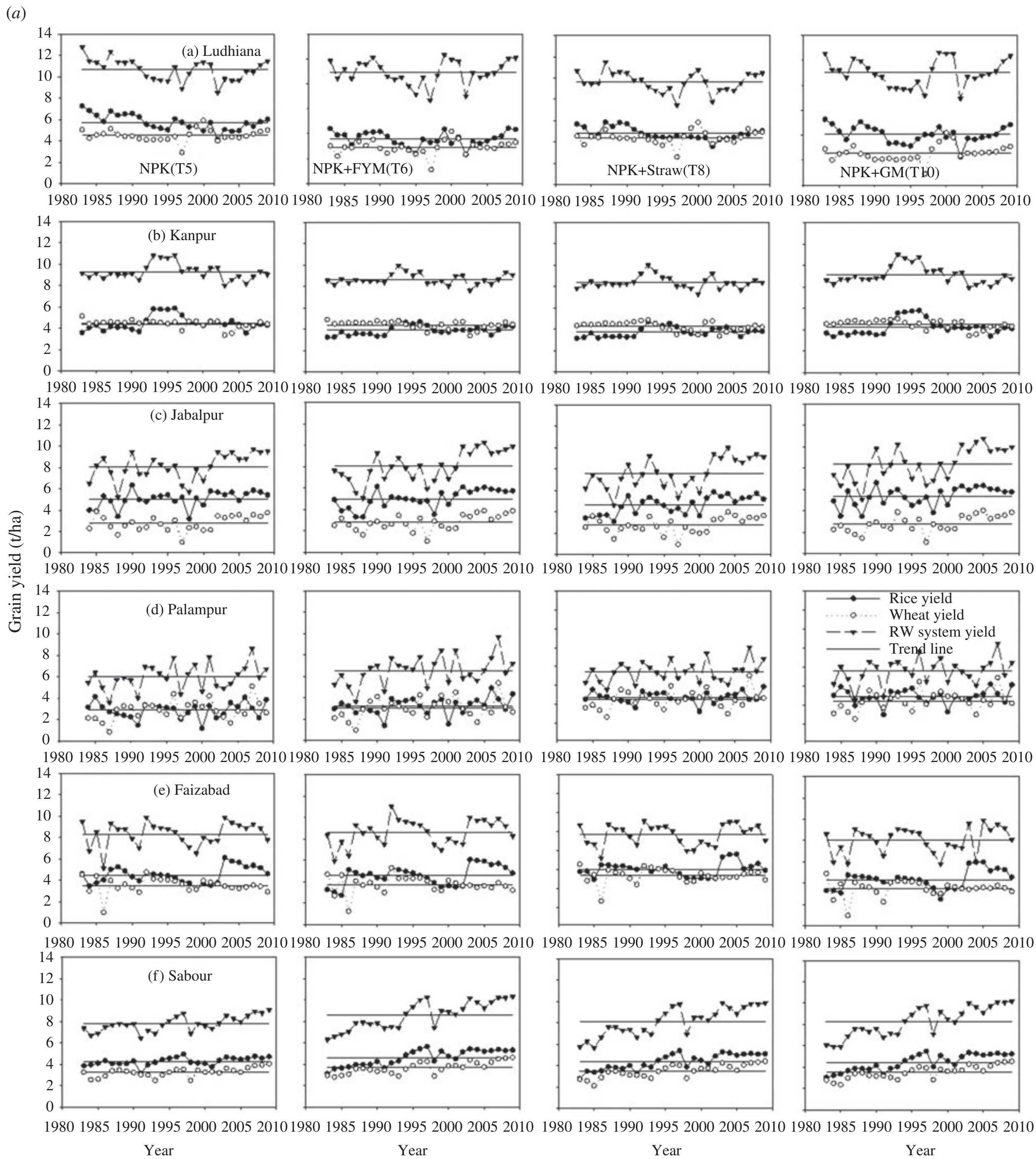

Fig. 2. For legend see next page.

(Fig. 3). At Palampur and Navsari, all the treatments except for farmers' practice showed lower yield response over the control during the last 3 years of the experiment (ending in 2009) compared with the initial 3 years. It was noted that at all the sites except Ludhiana and Palampur, wheat yield showed higher responses than the control during the 3 year to 2009 compared with the first 3 years of the experiment. For the rice–wheat system, at all the sites except Palampur and Navsari, all the treatments showed higher yield responses than the control during the 3 years to 2009 compared with the initial 3 years. This highlighted the

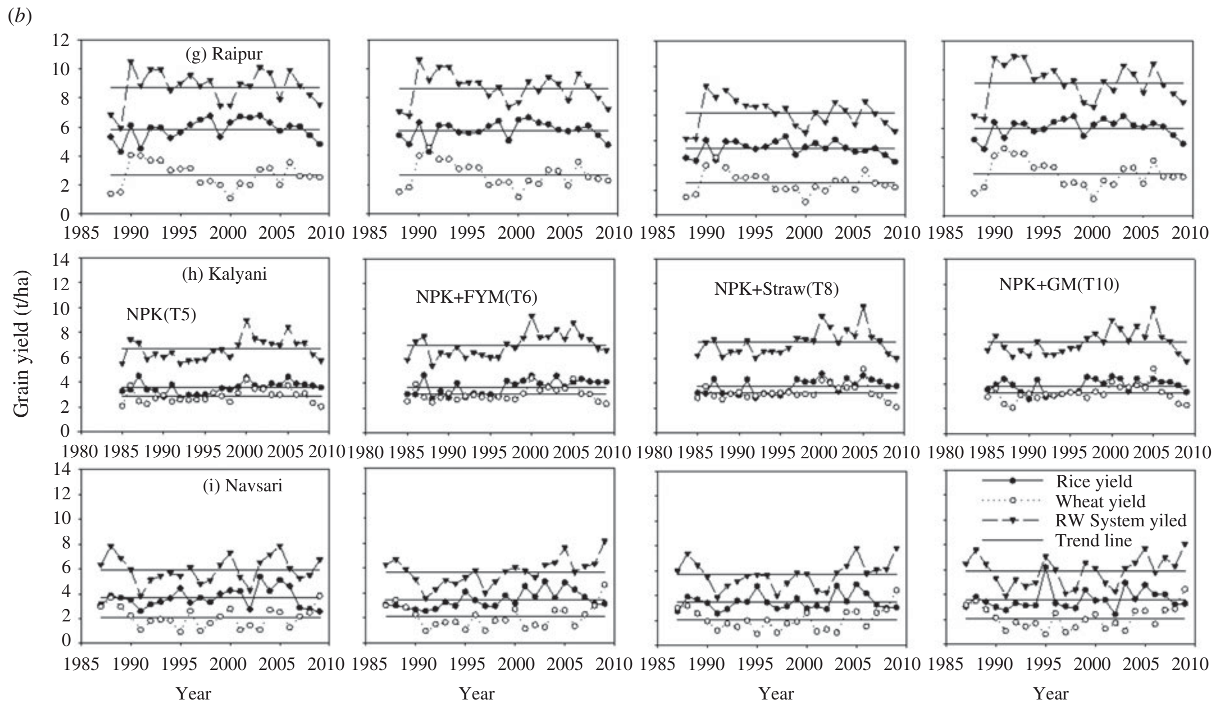

Fig. 2. Variability and trends (fitted by linear regression) of rice, wheat and rice–wheat system yield with the application of NPK, NPK+FYM, NPK+CR and NPK+GM nutrient treatments at (*a*) Ludhiana, (*b*) Kanpur, (*c*) Jabalpur, (*d*) Palampur, (*e*) Faizabad, (*f*) Sabour, (*g*) Raipur, (*h*) Kalyani and (*i*) Navsari.

need for modification of integrated nutrient management treatments with the incorporation of higher proportions of organic fertilizers (and therefore lower proportions of inorganic fertilizers). It also highlighted the need for modifications in the recommended dose of fertilizers.

However, the difference in deviations of rice yield responses over the recommended dose of fertilizer treatment was positive with the addition of organic fertilizers, except for application of inorganic treatments at different combinations and substitution of 0·25 N through CR in Ludhiana (Fig. 4). Interestingly, the difference in deviation was higher for farmers' practice. But in the case of wheat, all the treatments except for half the recommended dose of inorganic fertilizers were positive. For the rice–wheat system, all showed positive responses except for two treatments: 0·5 recommended dose of inorganic fertilizers in both seasons and 0·5 in the rice season only. It clearly showed that substituting FYM/CR/GM for inorganic N increased the yield compared with inorganic fertilizer alone over the duration of the experiment. The same pattern was also seen in Faizabad and Sabour. At all other sites, different treatments responded differently. At Navasari, the difference in the yield response over the recommended dose of fertilizer was positive in all treatments in the case of rice, wheat and the rice–wheat system.

Sustainability yield index

The SYI indicated that different integrated nutrient practices sustained the rice–what system productivity at different sites according to the nature of the climate (Table 13). There was a large difference in SYI between the control and other treatments. Rice yield was sustained at all the sites except Kanpur and Palampur with incorporation of FYM or GM to supplement the inorganic nutrient supply. Similarly, wheat yield as well as system productivity was sustained at all the sites except Kanpur and Navsari with incorporation of 0·5 N through FYM or GM.

Relation between weather variables and quantification of climate resilience management practices

Different integrated nutrient management practices responded differently to the excess/deficit quantity of monsoon rainfall at the different study sites (Table 14). The threshold rainfall value also varied from site to site

Table 11. *Comparison of initial and buildup of organic carbon and available N during the last 20 years of long-term experiment in rice–wheat system under different treatments over different study sites*

	Organic carbon (%)									Available nitrogen (kg/ha)								
Centre	Initial	T5	T6	T7	T8	T9	T10	T11	T12	Initial	T5	T6	T7	T8	T9	T10	T11	T12
Ludhiana	0·38	0·41	0·58	0·56	0·48	0·47	0·57	0·56	0·56	134	193	241	230	215	211	242	239	225
Kanpur	0·24	0·49	0·57	0·66	0·56	0·50	0·48	0·62	0·55	ND	ND	ND	ND	ND	ND	ND	ND	ND
Jabalpur	0·65	0·68	0·76	0·74	0·74	0·75	0·78	0·76	0·73	240	273	290	283	285	284	296	285	278
Palampur	0·60	0·72	0·85	0·80	0·80	0·80	0·82	0·70	0·72	667	255	284	256	240	234	257	243	221
Faizabad	0·37	0·54	0·64	0·58	0·56	0·57	0·60	0·58	0·36	102	183	216	227	192	201	222	218	164
Sabour	0·46	0·57	0·56	0·56	0·58	0·58	0·56	0·54	0·56	194	210	194	192	196	208	209	199	200
Raipur	0·51	0·68	0·66	0·65	0·60	0·59	0·69	0·68	0·58	234	261	259	251	251	244	272	268	231
Kalyani	0·52	0·75	0·75	0·60	0·57	0·78	0·87	0·90	0·45	106	154	148	129	129	129	117	120	111
Navasari	0·58	0·57	0·64	0·60	0·65	0·62	0·63	0·59	0·57	297	242	261	254	261	251	257	254	232

Compiled from Annual reports of AICRP-IFS centres during 2011/12; ND, no data available.

Table 12. *Comparison of initial and buildup of P and K during the last 20 years of long-term experiment in rice–wheat system under different treatments over different study sites*

	Available phosphorous (kg/ha)									Available potassium (kg/ha)								
Centre	Initial	T5	T6	T7	T8	T9	T10	T11	T12	Initial	T5	T6	T7	T8	T9	T10	T11	T12
Ludhiana	27	30	38	40	28	28	36	34	41	179	113	170	160	140	133	149	139	156
kanpur	10	22	27	25	23	22	23	25	25	170	151	175	166	160	165	164	170	169
Jabalpur	16	14	16	16	16	16	18	17	15	448	420	440	432	470	463	478	475	431
Palampur	22	70	81	64	68	54	66	71	66	221	153	166	157	162	154	150	147	158
Faizabad	14	21	24	23	20	20	24	23	18	355	258	253	261	266	255	244	256	220
Sabour	23	27	25	26	28	29	28	27	28	155	219	209	213	216	218	217	217	219
Raipur	12	30	26	27	23	21	29	26	22	280	278	287	290	270	261	294	283	247
Kalyani	29	81	83	78	62	66	64	73	46	288	308	286	264	255	246	264	273	238
Navasari	29	31	36	33	35	32	34	31	29	317	193	217	207	214	207	210	203	182

Compiled from Annual reports of AICRP-IFS centres during 2011/12.

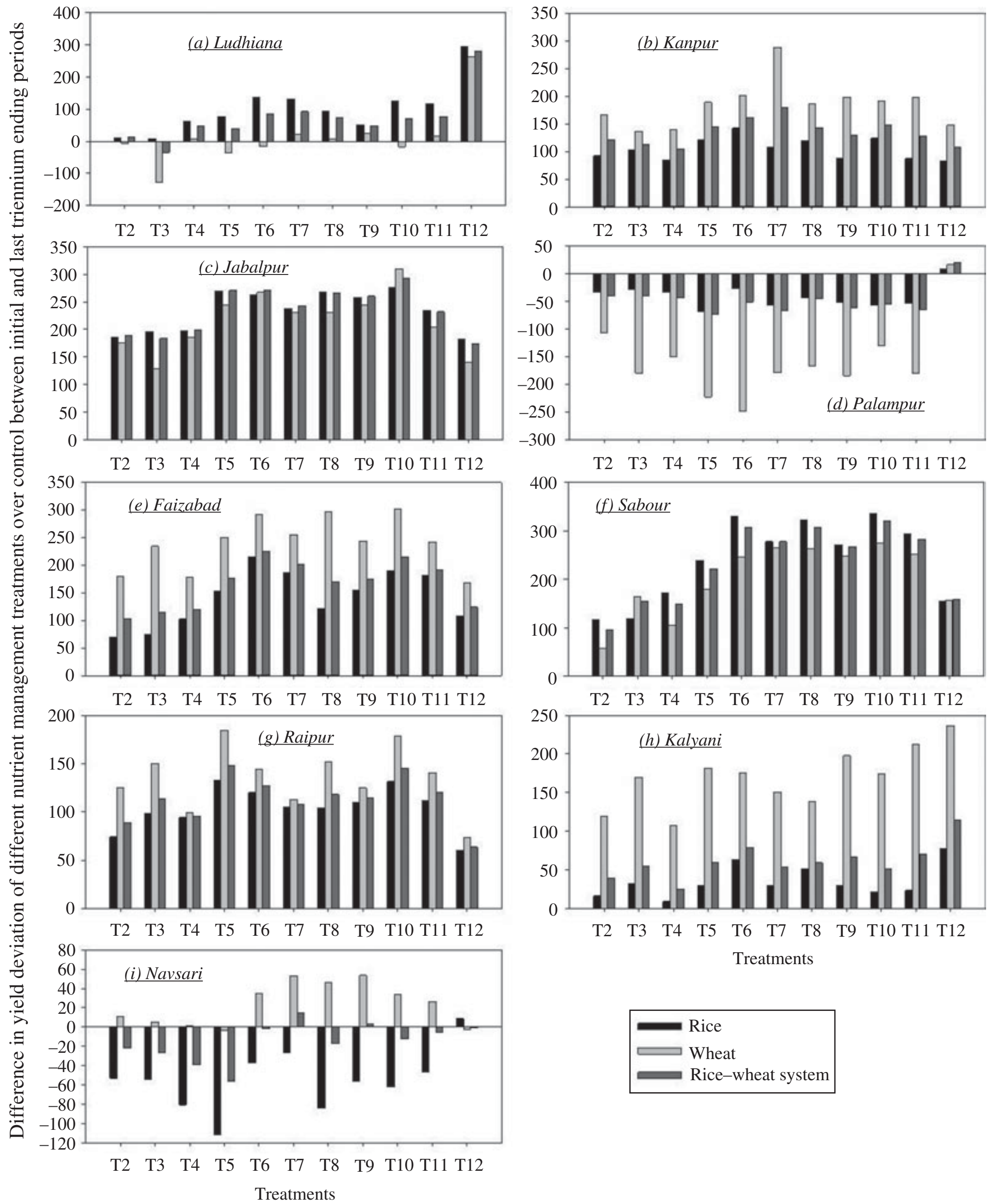

Fig. 3. Difference in yield deviation of different nutrient management treatments over the control between the first and last 3 years of long-term experiments at the selected study sites.

because of differences in mean seasonal rainfall, varying from 615·2 mm at Ludhiana to 1717·7 mm at Palampur with different SD, varying from 222·8 mm at Faizabad to 478 mm at Navsari. At Kanpur and Jabalpur, application of 0·5 of total N through FYM produced positive system yield anomalies of 0·2 and 0·7%, respectively. Application of 0·5 of total N through CR along with inorganic fertilizers produced a positive and higher yield anomaly at Raipur and Navsari during excess rainfall years. In Faizabad, a lower average yield anomaly of 1·2% was seen under both excess and deficit rainfall years with the application of 0·5 of total N through FYM. The threshold maximum temperature varied with the study site, from 20·6 °C at Palampur to 33·4 °C at Navsari, indicatative of the broad thermal wheat growing environmental situation that exists throughout the country (Table 15). The system yield deviation revealed that there is no uniform integrated nutrient management practice to withstand the extreme climatic

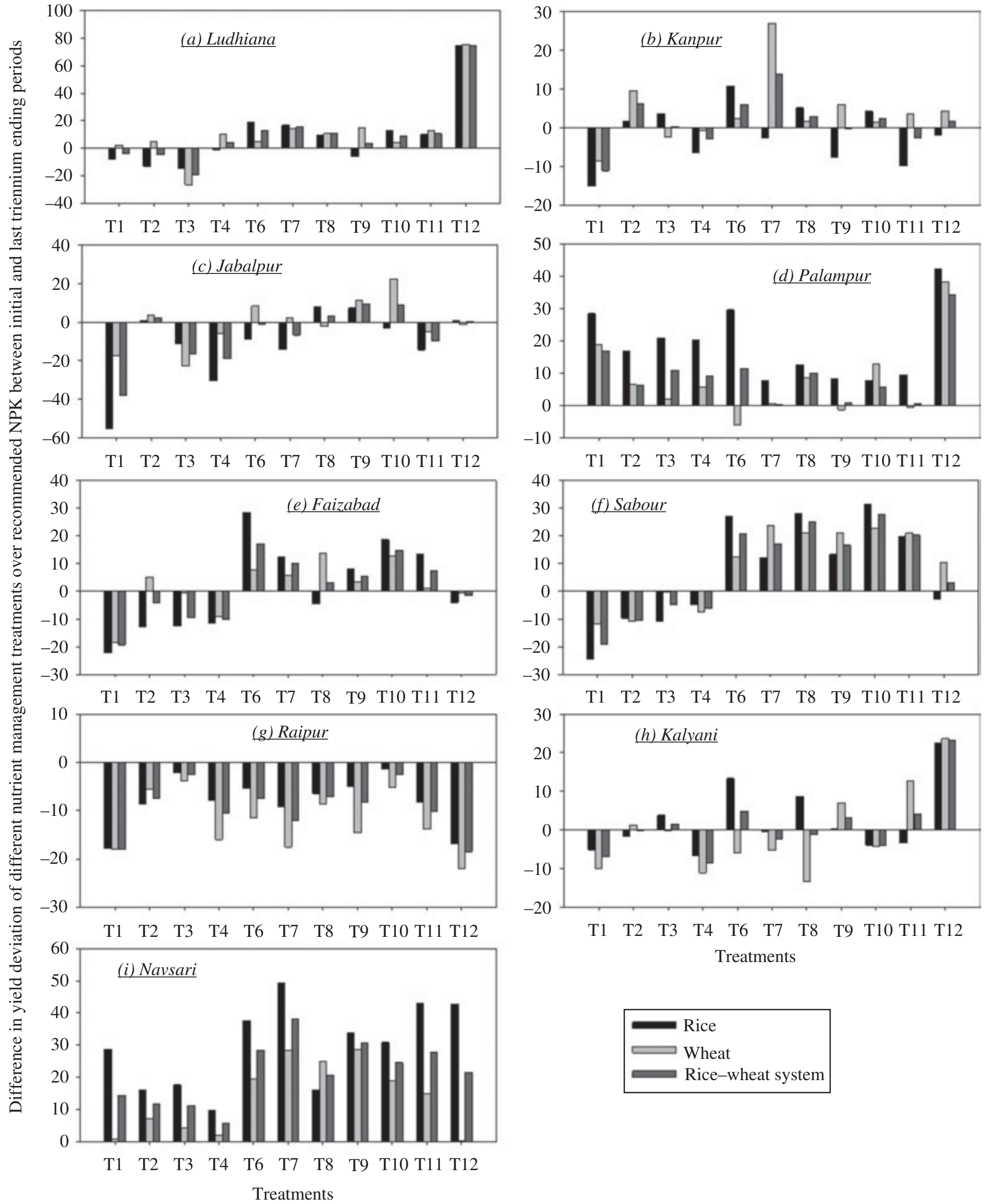

Fig. 4. Difference in yield deviation of different nutrient management treatments over recommended NPK between the first and last 3 years of long-term experiments at selected study sites.

situations across the study locations (Fig. 5). For the rice–wheat system, the simple average of rice yield anomaly and wheat yield anomaly indices (the RW anomaly index) was calculated for each treatment at all of the nine sites. The highest value of the RW anomaly index indicated the highest adaptive capacity of the treatment for sustainability under extreme climatic situations. Based on this index, three climate-smart nutrient management practices for rice–wheat systems were identified for each study site (Table 16).

DISCUSSION

Quantification of rainfall variability on rice yield under different nutrient management practices

Rice yields are influenced strongly by monsoon rainfall, which accounts for 0·67 of the variation in productivity over India (Subash & Ram Mohan 2010). When seasonal rainfall >750 mm at Ludhiana, the farmers' practice treatment produced the highest yield anomaly of 3·3% and the control treatment

Table 13. *Sustainable yield index (SYI) of rice, wheat and rice–wheat under different nutrient management practices for the study sites*

	Ludhiana			Kanpur			Jabalpur		
Treatments	Rice	Wheat	RW system	Rice	Wheat	RW system	Rice	Wheat	RW system
T1	0·20	0·18	0·23	0·18	0·18	0·19	0·24	0·14	0·22
T2	0·40	0·44	0·49	0·42	0·51	0·50	0·44	0·32	0·43
T3	0·45	0·53	0·57	0·44	0·65	0·60	0·50	0·44	0·51
T4	0·56	0·56	0·65	0·52	0·63	0·62	0·58	0·40	0·54
T5	0·64	0·65	0·75	0·62	0·79	0·76	0·65	0·51	0·64
T6	0·64	0·70	0·77	0·56	0·78	0·73	0·62	0·51	0·61
T7	0·64	0·63	0·74	0·58	0·65	0·68	0·65	0·47	0·62
T8	0·54	0·62	0·67	0·54	0·75	0·70	0·57	0·49	0·57
T9	0·58	0·56	0·67	0·55	0·71	0·69	0·57	0·42	0·54
T10	0·69	0·63	0·77	0·57	0·79	0·74	0·67	0·50	0·64
T11	0·70	0·60	0·76	0·59	0·76	0·74	0·66	0·45	0·62
T12	0·41	0·33	0·43	0·47	0·58	0·56	0·40	0·30	0·38
	Palampur			Faizabad			Sabour		
T1	0·31	0·09	0·23	0·19	0·09	0·17	0·20	0·16	0·19
T2	0·42	0·22	0·38	0·43	0·32	0·44	0·44	0·37	0·43
T3	0·38	0·27	0·40	0·44	0·50	0·54	0·46	0·58	0·56
T4	0·44	0·25	0·42	0·51	0·42	0·55	0·56	0·52	0·58
T5	0·44	0·36	0·49	0·60	0·53	0·65	0·69	0·61	0·68
T6	0·50	0·38	0·54	0·58	0·56	0·67	0·69	0·67	0·71
T7	0·45	0·31	0·47	0·61	0·48	0·64	0·70	0·58	0·67
T8	0·44	0·29	0·45	0·53	0·49	0·60	0·64	0·63	0·66
T9	0·43	0·27	0·42	0·54	0·45	0·59	0·64	0·57	0·64
T10	0·44	0·27	0·44	0·55	0·52	0·63	0·65	0·63	0·67
T11	0·46	0·27	0·44	0·56	0·47	0·61	0·65	0·58	0·64
T12	0·44	0·20	0·37	0·44	0·33	0·46	0·48	0·38	0·46
	Raipur			Kalyani			Navsari		
T1	0·26	0·13	0·23	0·22	0·10	0·18	0·23	0·14	0·28
T2	0·54	0·29	0·51	0·42	0·21	0·34	0·36	0·22	0·46
T3	0·59	0·34	0·57	0·43	0·42	0·47	0·38	0·27	0·5
T4	0·66	0·31	0·59	0·50	0·40	0·48	0·42	0·25	0·52
T5	0·75	0·39	0·69	0·57	0·45	0·55	0·47	0·27	0·57
T6	0·75	0·39	0·69	0·57	0·49	0·58	0·44	0·25	0·54
T7	0·74	0·34	0·65	0·62	0·45	0·57	0·46	0·23	0·54
T8	0·70	0·38	0·64	0·58	0·51	0·59	0·45	0·25	0·54
T9	0·71	0·35	0·65	0·56	0·45	0·55	0·48	0·23	0·54
T10	0·79	0·41	0·72	0·61	0·50	0·60	0·45	0·26	0·54
T11	0·77	0·37	0·69	0·60	0·42	0·56	0·49	0·21	0·53
T12	0·61	0·29	0·53	0·43	0·36	0·43	0·33	0·23	0·45

RW system: rice–wheat system.

produced an anomaly of −4·5%, while during drought years (rainfall <481 mm), all treatments except the application of 0·5 recommended dose of inorganic fertilizer during both the rice and wheat growing seasons recorded negative yield anomalies. This shows that there is no uniform nutrient management practice that will provide sustainable yields during both rainfall deficit or excess years. However, it can be said that on average, the farmers' practice produced a slightly higher yield anomaly compared with all the other treatments investigated. This could be due to the addition of 0·5 of total N through FYM (with the remaining N being supplied through inorganic fertilizers), which increased the moisture retention capacity of the soil (Srinivasarao *et al*. 2012*a*) and therefore the amount of water available to the crop during the

Table 14. *The average rice yield anomaly (%) pertaining to the years with extreme rainfall (mean ±0·5 SD) from estimated trends under different nutrient management treatments*

	Average yield deviation (%) from normal when rainfall (mm)								
	Ludhiana			Kanpur			Jabalpur		
Treatments	>750	<481	Mean	>967	<673	Mean	>1444	<1108	Mean
T1	−4·5	−2·0	−3·2	−0·1	−13·5	−6·8	+6·7	−19·0	−6·2
T2	−0·7	+1·3	+0·3	−2·8	−12·6	−7·7	+3·0	−7·0	−2·0
T3	−0·4	−1·1	−0·7	−4·4	−9·0	−6·7	+5·3	−6·8	−0·7
T4	+2·1	−2·9	−0·4	−4·1	−8·0	−6·1	+5·3	−9·7	−2·2
T5	+1·1	−2·0	−0·5	−2·0	−0·5	−1·2	+3·2	−9·1	−2·9
T6	−0·2	−1·6	−0·9	+0·9	−0·4	+0·2	+8·2	−6·9	+0·7
T7	+0·4	−3·1	−1·4	−0·5	−2·1	−1·3	+4·6	−7·8	−1·6
T8	−1·3	+1·6	+0·1	−0·3	−1·4	−0·8	+6·7	−7·6	−0·4
T9	+0·7	−1·5	−0·4	+0·4	−1·6	−0·6	+7·7	−9·1	−0·7
T10	+0·3	−2·5	−1·1	−4·4	−0·5	−2·5	+6·5	−7·9	−0·7
T11	+0·6	−3·2	−1·3	−3·5	−1·3	−2·4	+5·4	−9·0	−1·8
T12	+3·3	−2·5	0·4	−7·6	−10·8	−9·2	+2·0	−8·8	−3·4
		Palampur			Faizabad			Sabour	
	>1948	<1487	Mean	>948	<725	Mean	>1194	<934	Mean
T1	+2·4	−11·6	−4·6	0·0	−19·2	−9·6	−2·7	+6·9	+2·1
T2	+8·2	−6·1	+1·0	−0·8	−6·2	−3·5	+7·0	−0·5	+3·2
T3	+8·3	−5·4	+1·5	−4·1	−4·2	−4·2	+8·4	+0·6	+4·5
T4	+9·0	−3·9	+2·5	+0·4	−7·5	−3·5	+3·6	+1·6	+2·6
T5	+13·0	−6·5	+3·3	−0·6	−3·3	−2·0	+0·8	+0·8	+0·8
T6	+8·3	−7·7	+0·3	−2·7	+0·3	−1·2	+3·1	−0·6	+1·3
T7	+14·0	−6·1	+3·9	+2·7	−6·3	−1·8	−0·5	−0·2	−0·4
T8	+7·4	−5·3	+1·0	−1·5	−6·1	−3·8	+2·4	−0·3	+1·0
T9	+8·8	−2·3	+3·3	+1·8	−7·1	−2·6	+2·8	+1·3	+2·1
T10	+15·5	−8·1	+3·7	−3·1	−4·1	−3·6	+2·3	+0·1	+1·2
T11	+9·2	−3·9	+2·6	+0·8	−9·7	−4·4	+1·5	−0·8	+0·3
T12	−3·1	−3·6	−3·3	−2·6	−7·3	−5·0	+0·6	−2·6	−1·0
		Raipur			Kalyani			Navsari	
	>1168	<857	Mean	>1285	<964	Mean	>1816	<1338	Mean
T1	−2·2	−8·1	−5·1	+3·6	−3·1	+0·2	+1·4	−3·5	−1·1
T2	+3·1	−7·9	−2·4	−0·9	−2·0	−1·5	+3·5	−1·5	+1·0
T3	+4·8	−5·8	−0·5	+0·8	−3·5	−1·4	+4·0	−1·6	+1·2
T4	+3·7	−6·2	−1·2	+0·3	−2·8	−1·3	+6·9	−6·0	+0·5
T5	+2·9	−4·5	−0·8	−1·6	−1·1	−1·3	+6·0	−2·3	+1·9
T6	+3·6	−3·0	+0·3	−2·3	+2·2	−0·1	+3·0	−1·0	+1·0
T7	+1·6	−4·8	−1·6	−1·2	−3·0	−2·1	+4·6	−0·6	+2·0
T8	+5·4	−4·8	+0·3	−0·8	−2·2	−1·5	+9·4	−3·3	+3·0
T9	+3·8	−4·1	−0·1	−4·4	−1·6	−3·0	+5·8	−4·1	+0·8
T10	+4·2	−4·1	+0·1	−2·2	−4·1	−3·2	+5·7	−0·2	+2·7
T11	+2·2	−3·1	−0·5	−5·0	−2·8	−3·9	+2·3	−0·4	+1·0
T12	+5·1	−4·2	+0·4	−4·5	−3·1	−3·8	+3·2	+1·3	+2·2

sensitive phases of crop growth and development. In plots treated with FYM there may have been an overall improvement in nutrient supply via timed realase and more availability for crop uptake (Srinivasarao *et al.* 2012*b*).

Quantification of temperature variability on wheat yield under different nutrient management practices

Possible losses of 4–5 million tonnes of wheat could be seen with every 1 °C rise in temperature throughout

Table 15. *The average wheat yield anomaly (%) pertaining to the years when the maximum temperature during the wheat season ⩾ mean + 1 °C under different nutrient management treatments over different study sites*

	Average yield deviation from normal (%) when maximum temperature (°C)								
Treatments	Ludhiana ⩾ 25·6	Kanpur ⩾ 28·6	Jabalpur ⩾ 30·6	Palampur ⩾ 20·6	Faizabad ⩾ 29·2	Sabour ⩾ 28·8	Raipur ⩾ 32·8	Kalyani ⩾ 31·3	Navsari ⩾ 33·4
T1	−15·0	−3·7	−10·0	−9·0	−13·0	−15·0	−20·4	−20·3	−35·1
T2	−13·8	−3·1	−12·0	+2·6	−0·6	−13·5	−21·6	−19·5	−4·9
T3	−11·9	−2·3	−9·8	+3·1	−6·1	−14·2	−21·7	−13·2	−11·0
T4	−7·4	−3·9	−6·0	+2·3	−1·1	−7·5	−26·1	−7·3	−4·2
T5	−7·1	−1·9	−6·0	−0·2	−3·0	−4·0	−19·6	−6·3	−9·1
T6	−3·0	+1·9	−3·0	+3·7	+0·9	−3·0	−16·4	−4·5	−1·2
T7	−5·0	−1·4	−5·0	+2·0	+4·8	−5·0	−14·6	−6·7	+0·7
T8	−2·1	−2·5	−4·0	−0·1	+0·4	+3·2	−17·5	−5·4	−4·0
T9	−4·0	−4·0	−3·9	+6·3	−2·1	−7·0	−14·6	−7·4	−2·8
T10	+1·5	−1·8	−4·5	+4·9	+7·8	−1·9	−23·6	−8·3	−4·9
T11	−0·5	−2·7	−7·0	−0·9	+4·6	−2·3	−23·4	−6·2	+3·0
T12	−6·5	−2·5	−17·0	−12·0	−13·2	−10·9	−27·2	−10·7	−12·3

the growing period in India, even after considering enhanced carbon accumulation but no other adaptation benefits (Aggarwal *et al*. 2010). In the present study, when the average maximum temperature during the wheat season in a particular year increased to 1 °C or higher from the mean, the nutrient management treatments responded differently. In Ludhiana, all the treatments except application of 0·5 of total N through GM recorded negative yield anomalies, with declines ranging from −15% under the control treatment to −0·5% with the application of 0·25 N through GM. It was also noted that there was a yield anomaly of −7·1% with the recommended full dose of inorganic fertilizer. Gupta *et al*. (2010) also reported that an abrupt rise in temperature during the year 2010 produced an average yield penalty of −3·6% in Ludhiana. This reduction may be due to earlier grain filling and forced maturity, leading to a reduction in grain size and consequently yield (Rahman *et al*. 2009; Farooq *et al*. 2011; Lobell *et al*. 2012). In Kanpur, application of 0·5 of total N through FYM produced 1·9% higher yield anomaly while all other treatments recorded negative anomalies ranging from −4 to −1·4%. However, all the treatments show different magnitudes of negative yield anomalies at Jabalpur, Raipur and Kalyani. Application of 0·25 of total N through CR produced a 6·3% higher yield at Palampur. However, application of 0·25 N through GM produced a 3% higher yield anomaly in Navsari. This clearly shows that substitution of organic fertilizers such as FYM, CR or GM along with inorganic sources of nutrient supply reduced the negative effects of higher maximum temperature. However, the best type of organic manure depends upon the soil and climatic characteristics of the site.

Detection of site-specific climate-smart nutrient management practice for rice–wheat system

The system yield deviation revealed that there is no uniform integrated nutrient management practice to withstand the extreme climatic situations across the study locations. For example, at Ludhiana, it was found in the present study that the treatment of 0·5 recommended dose of NPK through chemical fertilizers and 0·5 N through GM resulted in an overall average increase of 1·5% in system yield under both excess (>750 mm) and deficit (<481 mm) rainfall conditions and also during the years with seasonal mean maximum temperature ⩾25·6 °C. Thus, this treatment has the adaptive capacity to withstand extreme climates and it can be said that this treatment is the primary climate-smart integrated nutrient management practice for rice–wheat system at Ludhiana. Treatments with application of 0·5 of total N through CR and 0·25 through GM were the second and third best climate-smart integrated nutrient management practices identified at Ludhiana. It was also found that the productivity of all 12 treatment systems was

Table 16. *Site-specific primary, secondary and tertiary climate-smart integrated nutrient management practices*

Site	Primary	Secondary	Tertiary
Ludhiana	0·50 NPK+0·50 N GM	0·50 NPK+0·50 N Straw	0·75 NPK+0·25 N GM
Kanpur	0·50 NPK+0·50 N FYM	0·75 NPK+0·25 N FYM	0·50 NPK+0·50 N GM
Jabalpur	0·50 NPK+0·50 N FYM	0·50 NPK+0·50 N CR	0·75 NPK+0·25 N CR
Palampur	0·75 NPK+0·25 N CR	0·50 NPK+0·50 N GM	0·75 NPK+0·25 N FYM
Faizabad	0·50 NPK+0·50 N GM	0·75 NPK+0·25 N FYM	0·50 NPK+0·50 N FYM
Sabour	0·50 NPK+0·50 N CR	0·50 NPK+0·50 N GM	0·50 NPK+0·50 N FYM
Raipur	0·75 NPK+25% N CR	0·50 NPK+0·50 N FYM	0·50 NPK+0·50 N CR
Kalyani	0·50 NPK+0·50 N FYM	0·50 NPK+0·50 N CR	1·00 NPK
Navsari	0·75 NPK+0·25 N GM	0·75 NPK+0·25 N FYM	0·50 NPK+0·50 N CR

NPK, inorganic fertilizers; FYM, farmyard manure; GM, green manure; CR, crop residue of wheat.

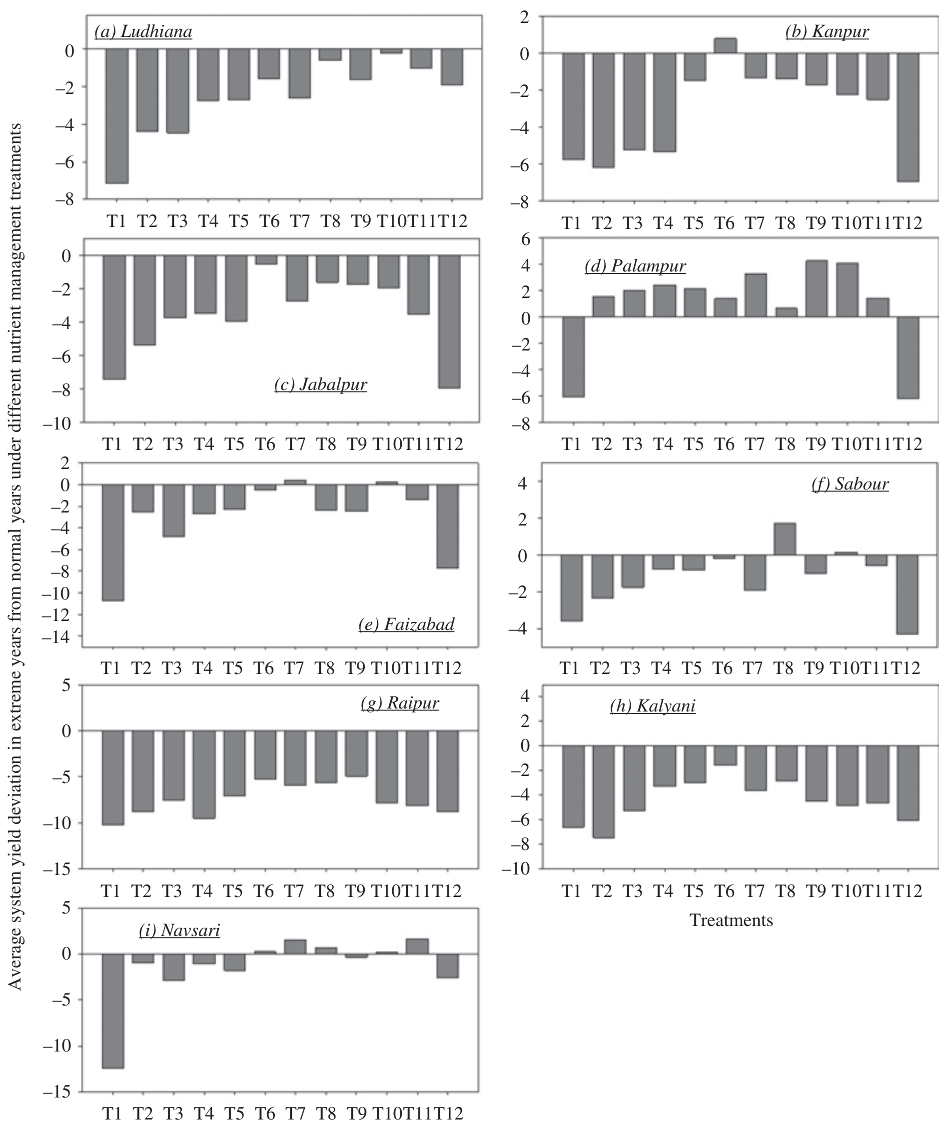

Fig. 5. Average percent deviation of rice-wheat system yield during failure/excess of monsoon years during *rice* and higher maximum temperature during wheat season over normal years at selected study locations.

affected negatively by the extreme climatic situations at Jabalpur, Raipur and Kalyani.

CONCLUSIONS

Significant observational changes were noticed in seasonal weather, i.e. monthly rainfall, maximum temperature, minimum temperature and sunshine hours at some of the study sites. Rice yields showed a significant decreasing trend (0·06 t/ha/year) at Ludhiana, which contributed to the significant decreasing trend of system yield (0·055 t/ha/year) even with the slight increasing trend of wheat yield under the recommended dose of inorganic fertilizers. Higher sustainable system yields were attained by the application of different combinations of integrated nutrient management (using a range of organic N sources) at the different study sites. The decreasing yield response to application of either inorganic fertilizer alone or inorganic fertilizer in combination with organic N sources (CR/FYM/GM) over unfertilized plots as well as a proportion of the recommended dose of inorganic fertilizers between the average yield level of the first 3 years of the experiment to the 3 years ending in 2009 at some of the sites accentuate the need for modification of integrated nutrient management treatments with the incorporation of higher organic fertilizers as the nutrient source. This also highlights the need for modifications in the recommended dose of fertilizers at these sites. The quantified system yield deviation under extreme climatic conditions and different nutrient management practices emphasized the importance of site-specific integrated nutrient management practices to overcome the negative effects of extreme climatic situations in the rice–wheat production system. The identification the top three site-specific climate-resilient nutrient management practices at the study sites provides an opportunity for the farming community to choose different organic fertilizers according to availability.

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