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Field Crops Research 81 (2003) 159–180
Field Crops Research
www.elsevier.com/locate/fcr

How extensive are yield declines in long-term rice–wheat experiments in Asia?

J.K. Ladha[a,*], D. Dawe[a], H. Pathak[b], A.T. Padre[a], R.L. Yadav[c], Bijay Singh[d], Yadvinder Singh[d], Y. Singh[e], P. Singh[f], A.L. Kundu[g], R. Sakal[h], N. Ram[e], A.P. Regmi[i], S.K. Gami[j], A.L. Bhandari[d], R. Amin[k], C.R. Yadav[l], E.M. Bhattarai[m], S. Das[n], H.P. Aggarwal[o], R.K. Gupta[p], P.R. Hobbs[q]

[a]*International Rice Research Institute (IRRI), DAPO Box 7777, Metro Manila, Philippines*
[b]*Indian Agricultural Research Institute, New Delhi 110 012, India*
[c]*Project Directorate for Cropping System Research, Modipuram, Meerut 250 110, India*
[d]*Punjab Agricultural University, Ludhiana 141 004, India*
[e]*G.B. Pant University of Agriculture and Technology, Pantnagar 263 145, India*
[f]*Jawaharlal Nehru Krishi Viswavidyalaya, Regional Agricultural Research Station, Rewa 486 001, India*
[g]*Bidhan Chandra Krishi Vishwavidyalaya, Mohanpur, Nadia 741 252, India*
[h]*Rajendra Agricultural University, Pusa, Samastipur 848 125, India*
[i]*Regional Agricultural Research Station, Bhairahwa, Nepal*
[j]*Regional Agricultural Research Station, Parwanipur, Nepal*
[k]*Wheat Research Center, Dinajpur 5200, Bangladesh*
[l]*Regional Agricultural Research Station, Tarahara, Sunsari, Nepal*
[m]*Regional Agricultural Research Station, Nepalgunj, Nepal*
[n]*Fertilizer Association of India, New Delhi 110 016, India*
[o]*Institute of Agricultural Sciences, Banaras Hindu University, Varanasi 221 005, India*
[p]*Rice–Wheat Consortium for Indo-Gangetic Plains, IARI Campus, New Delhi 110 012, India*
[q]*The International Maize and Wheat Improvement Center (CIMMYT), P.O. Box 5186, Kathmandu, Nepal*

Received 25 February 2002; received in revised form 4 November 2002; accepted 5 November 2002

Abstract

The rice–wheat cropping system, occupying 24 million hectares of the productive area in South Asia and China, is important for food security. Monitoring long-term changes in crop yields and identifying the factors associated with such changes are essential to maintain and/or improve crop productivity. Long-term experiments (LTE) provide these opportunities. We analyzed 33 rice–wheat LTE in the Indo-Gangetic Plains (IGP) of South Asia, non-IGP in India, and China to investigate the extent of yield stagnation or decline and identify possible causes of yield decline. In treatments where recommended rates of N, P and K were applied, yields of rice and wheat stagnated in 72 and 85% of the LTE, respectively, while 22 and 6% of the LTE showed a significant ($P < 0.05$) declining trend for rice and wheat yields, respectively. In the rice–wheat system, particularly in the IGP, rice yields are declining more rapidly than wheat. The causes of yield decline are mostly location-specific but depletion of soil K

Abbreviations: FYM, farmyard manure; GM, green manure; ICAR, Indian Council of Agricultural Research; IGP, Indo-Gangetic Plains; LTE, long-term experiment; RW, rice–wheat system; SOM, soil organic matter

* Corresponding author. Tel.: +63-2845-0563; fax: +63-2891-1292.
E-mail address: j.k.ladha@cgiar.org (J.K. Ladha).

PII: S0378-4290(02)00219-8

seems to be a general cause. In over 90% of the LTE, the fertilizer K rates used were not sufficient to sustain a neutral K input–output balance. Depletion of soil C, N and Zn and reduced availability of P, delays in planting, decreases in solar radiation and increases in minimum temperatures are the other potential causes of yield decline. A more efficient, integrated strategy with detailed data collection is required to identify the specific causes of yield decline. Constant monitoring of LTEs and analysis of the data using improved statistical and simulation tools should be done to unravel the cause–effect relationships of productivity and sustainability of rice–wheat systems.

Keywords: Indo-Gangetic plains; Long-term experiments; Nutrient budget; Rice–wheat system; Soil fertility; Yield decline; Yield trends

1. Introduction

The rice–wheat rotation is one of the largest agricultural production systems of the world, occupying 24 million hectares of productive land in the Indo-Gangetic Plains (IGP) in South Asia and in China. In South Asia, the rice–wheat system occupies about 13.5 million hectares (10 million in India, 2.2 million in Pakistan, 0.8 million in Bangladesh and 0.5 million in Nepal), extending across the Indo-Gangetic floodplain into the Himalayan foothills (Ladha et al., 2000). In addition, a substantial rice–wheat system area exists outside the IGP, in China (10.5 million hectares), India and Nepal. In India, the system includes hilly parts of Himachal Pradesh and Uttranchal, and parts of Jharkhand, Madhya Pradesh and Rajasthan. In China, the rice–wheat system is widely practised in the provinces of Jiangsu, Zhejiang, Hubei, Guizhou, Yunnan, Sichuan and Anhui. The characteristics of areas under rice–wheat in and outside the IGP, including China, are available elsewhere (Zheng, 2000; Narang and Virmani, 2001; Gupta et al., in press).

The rice–wheat system accounts for about one-third of the area of both rice and wheat grown in South Asia and its production provides staple grain for more than 400 million people, or about 8% of world's population. During the Green Revolution era, production increases resulted from increases in both rice–wheat area and system productivity. But little additional land is available now and traditional farmlands are increasingly lost to urbanization. In addition, since most of the land is already double- and even triple-cropped increasing cropping intensity is not a possible option for increasing production. Therefore, future demand for food will have to be met mainly through increases in production per unit of harvested area. Concerns are being raised as to whether degrading soil and water resources threaten the sustainability of this important production system (Byerlee and Siddiq, 1994; Hobbs and Morris, 1996; Sinha et al., 1998; Aggarwal et al., 2000a; Duxbury et al., 2000; Yadav et al., 2000a,b; Timsina and Connor, 2001; Bhandari et al., 2002; Byerlee et al., 2002; Ladha et al., in press).

It is essential that performance of the system be continuously monitored for productivity, soil nutrient stocks, and nutrient-supplying capacity to ensure and improve sustainability. Long-term experiments (LTE) provide opportunities for monitoring long-term changes in crop yields and nutrient balances, and identifying the factors associated with such changes. They also provide data on which to base rational judgments about the biophysical aspects of sustainability (Powlson et al., 1986). Many LTE were begun in the 1970s and 1980s in double- and triple-cropped rice–wheat systems, mostly in the IGP of South Asia and in China, to monitor yield trends and system sustainability. Analyses of yield trends in some of these LTE have mostly been published in several isolated publications with a few exceptions. Some efforts have been made to compile the analysis of various LTE (Dawe et al., 2000; Duxbury et al., 2000; Yadav et al., 2000a,b). However, this is the first attempt to make a combined analysis of existing LTE from diverse agroecological regions to facilitate global and regional interpretations using the most recent data and identical statistical procedures.

In the present paper, we report the analysis of yield trends of 33 LTE conducted at different sites in South Asia and China to investigate the extent and causes of yield stagnation or decline of rice and wheat. The paper includes the LTE reported by Dawe et al. (2000), Duxbury et al. (2000) and Yadav et al. (2000b) together with several other LTE and more recent data.

2. Data and methods

2.1. Experimental sites and treatments

We obtained the data of 33 LTE conducted at 21 different sites in India, Nepal, China and Bangladesh (Table 1). Of the 33 LTE, 23 cover four of the five transects of the IGP (except transect 1), 7 are from India outside of the IGP (Fig. 1) and 3 are from China. The LTE sites are located within subtropical to warm temperate climates characterized by cool and dry winters and warm and wet summers (Table 2). The IGP, where the majority of the LTE were located, is divided into five transects: (a) Trans-Gangetic Plains or IGP transects 1 and 2 (areas in Pakistan and parts of Punjab and Haryana in India), (b) Upper-Gangetic Plains or IGP transect 3 (most of Uttar Pradesh and parts of Bihar in India and parts of Nepal), (c) Middle-Gangetic Plains or IGP transect 4 (parts of Bihar in India and parts of Nepal), and (d) Lower-Gangetic Plains or transect 5 (parts of Bihar and West Bengal in India and parts of Bangladesh). The mean (15 years average) daily solar radiation decreases from transect 1 to 5 in the rice season and the trend is reversed in the wheat season. The minimum temperature in the rice and wheat seasons increases from transects 1 to 5. This is also true for the maximum temperature in the wheat season, but in the rice season the maximum temperature is similar throughout all IGP transects. Rainfall also follows a distinct pattern of increase from transects 1 to 5. Although transect 1 receives only 650 mm of rainfall per annum, transect 5 receives more than 2.5 times more rainfall than in transect 1. The climatic parameters, except rainfall, make transects 1 and 2

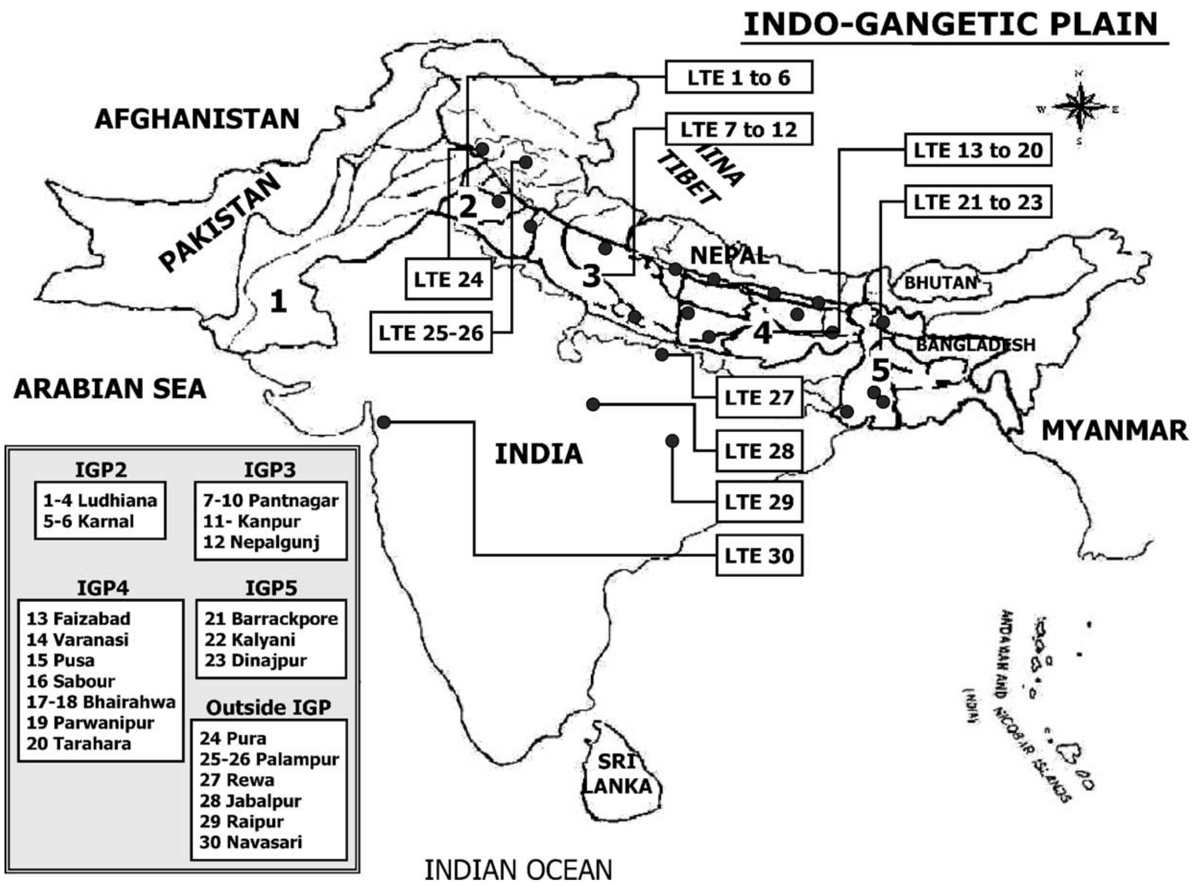

Fig. 1. Map showing the location of long-term rice–wheat experiments in the IGP of Bangladesh, India and Nepal.

Table 1
Long-term rice–wheat and rice–rice–wheat experiments in South Asia and China

LTE no.	Location			Experiment ID[a]	Soil type[b] (texture class)	Fertilizer rate[c] (N–P–K rice; N–P–K wheat)	Organic fertilizer[d]	Duration[e]	Reference[f]
	IGP	Country	Site						
1	2	India	Ludhiana 1	AICRP-CSR	Typic Ustochrept (LS)[h]	120–26–25; 120–26–25	None	1984–2001	Bhandari et al. (2002), Yadav et al. (2000b)
2	2	India	Ludhiana 2	Residue	Ustochrept (LS)	120–30–30; 120–60–30	Residue	1993–2000	Not available
3	2	India	Ludhiana 3	Phosphorus	Typic Ustochrept (LS)	150–26–25; 120–26–25	None	1991–2001	Singh et al. (2000), Dawe et al. (2000)
4	2	India	Ludhiana 4	Residue	Typic Ustipsamment (LS)	150–0–0; 150–26–50	None	1988–2000	Yadvinder Singh et al. (2000)
5	2	India	Karnal 1	Phosphorus	Aquic Natrustalf	120–22–50; 120–22–50	None	1976–1996	Chhabra and Thakur (2000)[g]
6	2	India	Karnal 2	AICRP-CSR	Aquic Natrustalf	120–22–42; 120–22–42	None	1974–1986	Singh and Swarup (2000), Dawe et al. (2000)
7	3	India	Pantnagar 1	AICRP-CSR	Aquic Hapludoll (SiCL)	120–26–37; 120–26–37	FYM	1972–1992	Ram (2000)
8	3	India	Pantnagar 2	LTE2(b)	Typic Hapludoll (L)	120–35–33; 120–35–33	None	1977–2000	Singh et al. (2000), Dawe et al. (2000)
9	3	India	Pantnagar 3	AICRP-CSR	Hapludoll (SiL)	120–26–33; 120–26–33	None	1983–2000	Yadav et al. (2000b)
10	3	India	Pantnagar 4	LTFE	Fluventic Haplaquoll (SiL)	120–17–33; 120–17–33	None	1984–1999	Dawe et al. (2000)
11	3	India	Kanpur	AICRP-CSR	Udic Ustochrepts	120–26–33; 120–26–33	None	1984–2000	Yadav et al. (2000b)
12	3	Nepal	Nepalgunj	LTSFE	Dystric Eutrochrept (SiL)	100–30–30; 100–30–30	None	1978–1998	Bhattarai and Mishra (1999)
13	4	India	Faizabad	AICRP-CSR	Udic Fluaquents (SiL)	120–26–33; 120–26–33	None	1984–1999	Yadav et al. (2000b)
14	4	India	Varanasi	AICRP-CSR	Aeric Ochroqualfs	120–26–33; 120–26–33	None	1985–2000	Yadav et al. (2000a)
15	4	India	Pusa		Ustochrept	150–33–60; 150–33–62	None	1985–1999	Sakal (2000)[g]
16	4	India	Sabour	AICRP-CSR	Ustochrept (clayey)	120–26–33; 120–26–33	None	1984–2000	Yadav et al. (2000b)
17	4	Nepal	Bhairahwa 1	LTSFE	Typic Haplaquepts (SL)	100–13–25; 100–18–25	None	1979–2000	Regmi et al. (2002a)
18	4	Nepal	Bhairahwa 2	LTSFE	Typic Haplaquepts (SL)	100–13–0; 100–13–0	FYM	1988–2000	Regmi et al. (2002b)
19	4	Nepal	Parwanipur	LTSFE	Inceptisol (LS)	100–13–25; 100–13–25	None	1980–2000	Gami et al. (2001)
20	4	Nepal	Tarahara	LTSFE	Typic Haplaquepts (L)	100–13–25; 100–17–25	None	1978–1997	Yadav et al. (1999)
21	5	India	Barrackpore	AICRP-LTE	Eutrochrept (SL)	180–39–75; 180–39–75	None	1973–1997	Saha et al. (2000), Dawe et al. (2000)
22	5	India	Kalyani	AICRP-CSR	Udic Ustochrepts	120–26–33; 120–26–33	None	1986–2000	Yadav et al. (2000b)
23	5	Bangladesh	Dinajpur		na[i]	135–80–120; 180–80–120	None	1992–2001	Badaruddin et al. (2000)
24	Non-IGP	India	RS Pura	AICRP-CSR	Eutrochrept (CL)	120–26–33; 120–26–33	None	1985–2000	Not available
25	Non-IGP	India	Palampur 1	AICRP-CSR	Udic Haplustalf	120–26–33; 120–26–33	None	1985–2000	Not available
26	Non-IGP	India	Palampur 2	LANTANA	Typic Hapludalf (SiCL)	90–18–33; 120–26–25	None	1988–2000	Sharma et al. (in press)
27	Non-IGP	India	Rewa		Typic Hapludalf (SiCL)	120–35–33; 120–35–33	None	1977–2000	Singh and Khan (2000)[g]
28	Non-IGP	India	Jabalpur	AICRP-CSR	Chromoustert (clayey)	120–26–33; 120–26–33	None	1985–2000	Yadav et al. (2000b)
29	Non-IGP	India	Raipur	AICRP-CSR	Ochraqualfs (clayey)	120–26–33; 120–26–33	None	1988–1999	Not available

30	Non-IGP	India	Navsari	AICRP-CSR	Vertic Ustochrept	120–26–33; 120–26–33	None	1987–2000	Not available
31	China	China	Nangong	LTFE	Paddy soil, river alluvium (SiCL)	120–17–33; 120–17–33	None	1983–1996	Lin and Li (1992), Dawe et al. (2000)
32	China	China	Sichuan	LTE	Purple paddy soil (L)	113–25–47; 188–41–78	None	1984–1998	Dawe et al. (2000)
33	China	China	Jiangsu	LTE	Sandy loam	150–19–90; 150–23–90	None	1985–1996	Zhuang (1999)

[a] AICRP-CSR, All India Coordinated Research Project on Cropping Systems Research; LTE, long-term experiment; LTFE, long-term fertilizer experiment; LTSFE, long-term soil fertility experiment.

[b] Soil classification using USDA Soil Taxonomy.

[c] Fertilizer rates given on elemental basis are the recommended rates which produced the yields reported in Tables 2–5. The LTEs involve other treatments representing different levels of mineral and organic fertilizer. For each experiment, the first row shows fertilizer rates for rice, the second row for wheat.

[d] Organic fertilizer applied together with inorganic NPK resulting in the yields reported in Tables 2–5. Residue refers to rice or wheat straw; FYM in Pantnagar 1 was added at 15 Mg ha^{-1}; FYM in Bhairahwa 2 was added at 4 Mg ha^{-1}.

[e] Duration of the experiment.

[f] Paper describing more experimental details and results.

[g] Data of the LTE were obtained from this publication.

[h] LS, loamy sand; L, loam; SL, sandy loam; CL, clay loam; SiL, silty loam; SiCL, silty clay loam.

[i] Not available.

Table 2
Characterization of long-term experimental sites in South Asia and China

LTE No.	Site	Latitude (°N)	Longtitude (°E)	Radiation (MJ m^{-2} per day)		Minimum temperature (°C)		Maximum temperature (°C)		Annual rainfall (mm)	Organic C[a] (%)	Olsen P[b] (mg kg^{-1})	Available K[c] (mg kg^{-1})
				Rice	Wheat	Rice	Wheat	Rice	Wheat				
1	Ludhiana 1	30.93	75.86	20.7	15.0	23.4	8.9	33.0	22.5	650	0.31	5	46
2	Ludhiana 2	30.93	75.86	20.7	15.0	23.4	8.9	33.0	22.5	650	0.31	5	46
3	Ludhiana 3	30.93	75.86	20.7	15.0	23.4	8.9	33.0	22.5	650	0.42	4	40
4	Ludhiana 4	30.93	75.86	20.7	15.0	23.4	8.9	33.0	22.5	650	0.36	10	38
5	Karnal 1	29.72	75.95	20.2	15.2	23.0	9.3	32.7	23.9	700	0.30	15	160
6	Karnal 2	29.72	75.95	20.2	15.2	23.0	9.3	32.7	23.9	700	0.30	15	160
7	Pantnagar 1	29.00	79.30	16.8	14.0	23.0	9.4	31.8	24.5	1350	1.48	18	125
8	Pantnagar 2	29.00	79.30	16.8	14.0	23.0	9.4	31.8	24.5	1430	1.42	9	65
9	Pantnagar 3	29.00	79.30	16.8	14.0	23.0	9.4	31.8	24.5	1350	1.42	9	65
10	Pantnagar 4	29.00	79.30	16.8	14.0	23.0	9.4	31.8	24.5	1350	1.42	9	65
11	Kanpur	25.43	80.57	16.1	16.2	26.0	14.0	36.0	29.0	818	0.39	6	82
12	Nepalgunj	28.05	81.62	na[d]	na	25.3	9.6	33.1	24.2	1539	1.50	30	155
13	Faizabad	26.67	82.13	18.3	15.7	24.6	11.0	32.1	26.3	1100	0.37	6	161
14	Varanasi	25.30	83.50	18.9	17.5	24.6	12.1	32.9	27.2	1100	0.42	20	109
15	Pusa	25.83	85.83	13.4	17.3	25.0	16.0	33.0	31.0	1100	0.45	9	45
16	Sabour	25.14	87.40	11.7	17.3	25.0	17.0	33.0	29.0	1200	0.46	5	60
17	Bhairahwa 1	27.53	83.47	11.4	12.5	24.0	11.0	32.0	26.0	1687	1.03	10	125
18	Bhairahwa 2	27.53	83.47	11.4	12.5	24.0	11.0	32.0	26.0	1687	1.03	10	125
19	Parwanipur	27.21	84.53	na	na	24.8	6.5	32.3	21.0	1600	0.65	15	54
20	Tarahara	26.45	87.20	na	na	22.0	10.6	33.5	22.6	1612	0.93	16	55
21	Barrackpore	22.75	88.43	10.8	17.0	26.0	18.0	33.0	31.0	1666	0.71	19	64
22	Kalyani	22.83	88.83	10.8	17.0	26.0	18.0	33.0	31.0	1600	0.92	7	36
23	Dinajpur	25.61	88.63	16.5	14.6	24.7	13.7	31.5	27.1	1680	0.80	na	na
24	Pura	32.80	74.13	na	na	na	na	na	na	500	0.62	6	71
25	Palampur 1	30.60	73.30	17.8	13.8	18.0	7.7	26.0	18.1	1200	0.6	10	100
26	Palampur 2	30.60	73.30	17.8	13.8	18.0	7.7	26.0	18.1	1200	1.10	6	66
27	Rewa	24.31	81.25	12.8	16.8	22.6	11.2	33.0	28.0	1222	0.66	5	225
28	Jabalpur	22.43	75.66	12.4	16.2	23.1	11.5	31.9	29.0	1447	0.69	9	318
29	Raipur	21.20	81.70	14.9	19.1	22.9	13.7	30.8	30.4	1388	0.65	6	167
30	Navsari	20.88	72.80	na	na	na	na	na	na	1226	0.62	17	150
31	Nangong	37.37	115.37	na	na	na	na	na	na	na	2.00	16	128
32	Sichuan	31.30	104.13	na	na	na	na	na	na	1065	na	na	na
33	Jiangsu	na	na	na	na	na	na	na	na	na	na	na	na

[a] Organic C content of soil was estimated by Walkley and Black (1934) method. Sources from references in Table 1, Abrol et al. (2000), and Gangwar and Kumar (1998).
[b] Olsen P content of soil was estimated by Olsen et al. (1954) method. Sources from references in Table 1, Abrol et al. (2000), and Gangwar and Kumar (1998).
[c] Available K of soil was estimated by ammonium acetate extraction method (Knudsen et al., 1982). Sources from references in Table 1.
[d] Not available.

more favorable for rice and wheat cultivation. Access to assured irrigation, however, helped overcome the problem of low rainfall and made the zone very productive, while the less favorable climatic conditions, i.e. lower solar radiation and higher minimum temperature and limited irrigation facilities and infrastructure are the bottlenecks to achieving higher yields in lower transects of the IGP. In the non-IGP regions, annual rainfall varies between 1200 and 1447 mm. Palampur, located in the north of transect 2 is cooler and Rewa, Jabalpur and Raipur located in the south of the IGP are warmer (Table 2).

Soil fertility varies widely across these LTE in terms of organic C (3–20 g kg^{-1}), Olsen P (0.005–0.030 g kg^{-1}) and available K (0.036–0.318 g kg^{-1}). Organic C content is generally higher in the soils of the lower than in those of the upper IGP (Table 2).

The LTE have a range of treatments representing different levels of mineral and organic fertilizer. However, for the present study, only data from the treatments with the recommended NPK rate were included because treatments with key macronutrients omitted represent incorrect nutrient management and are not suitable for assessing the sustainability of a cropping system (Dawe et al., 2000; Gami et al., 2001; Bhandari et al., 2002; Regmi et al., 2002a,b). Furthermore, such nutrient management is not practiced in farmers' fields and is of limited usefulness for assessing the practical importance of yield declines.

2.2. Crop management

Most of the experiments included two crops per year: rice grown in summer months (June–October) under monsoon climatic conditions and wheat grown during the cooler and drier winter months (November–March). The Bhairahwa 1, Dinajpur, Zhejiang and Sichuan LTE included three crops per year: early rice (April–July), late rice (July–November) and wheat (November–March).

All the LTE used semi-dwarf high-yielding cultivars of rice and wheat. The cultivars were exchanged during the course of the experiment for the best cultivar available in the region. Generally, two to three rice seedlings (4–5 weeks old) were transplanted in the puddled lowland field at 20 cm × 15 cm spacing. Normally the plots were flooded (2–4 cm) until 2 weeks before the rice harvest. Fertilizer doses used in different LTE are given in Table 1. All the P as single superphosphate or $(NH_4)_2HPO_4$ and K as KCl were applied as basal fertilizer on the day of planting. Nitrogen as $(NH_4)_2HPO_4$ or urea or both was applied in 2–3 splits, 50% at transplanting of rice and the remaining 1 or 2 splits topdressed at tillering and panicle initiation stages. Wheat (100–120 kg seed ha^{-1}) was sown in rows and 3–4 irrigations were given at sowing, crown root initiation, maximum tillering and flowering stages. All P and K and a half dose of N (Table 1) were applied at sowing. The remaining N was topdressed in 1–2 splits at crown root initiation and maximum tillering stages with irrigation.

Weeds, pests and diseases were controlled as required. Crops were harvested manually close to the ground using sickles and straw was removed from the field. Grain yield was measured at maturity and was adjusted to 140 and 120 g water kg^{-1} for rice and wheat, respectively. The data on soil and plant parameters were collected over time in the LTE but with widely differing frequencies. The details of the sampling and analytical procedures used in the experiments are given in various publications referring to the various LTE (Table 1).

2.3. Estimation of soil organic C, Olsen P and available K

Normally soil samples were collected at the start of the experiments from the 0–15 cm soil layer, sieved through a 2 mm screen, mixed, air dried and analyzed for organic C (Walkley and Black, 1934), Olsen P (Olsen et al., 1954), and exchangeable K (Knudsen et al., 1982). More details can be found in the respective publications cited in Table 1.

2.4. Nutrient budgets

Apparent annual average P and K balances were estimated for the 100% recommended NPK treatment using the method described by Bhandari et al. (2002) and Regmi et al. (2002a) considering various inputs (fertilizer, rain, irrigation water, seedlings/seeds, root biomass) and outputs (uptake, losses). Plant P and K were estimated using standard internal efficiencies for rice (Witt et al., 1999) and wheat (Pathak et al., 2002a). We assumed that there would be no loss of P through leaching or otherwise from the soil system.

Leaching loss of K was taken to be 150 g kg^{-1} of K input (Smaling and Fresco, 1993; Regmi et al., 2002a).

2.5. Data analyses

Linear regression analyses were done to determine trends (slopes) of grain yield over the years using SAS systems (SAS, 1995). The *P*-values and *t*-statistics on the slopes were used to test whether the observed changes were significantly different from 0 ($P < 0.05$). Rice and wheat yield responses to different levels of NPK application for the initial and final 3 years of some of the experiments were compared by doing simple linear regression analyses on each year's data of grain yield and NPK applied. The slopes and y intercepts were compared based on their 95% confidence intervals.

Table 3
Yield trends of rice in rice–wheat LTEs in different parts of the IGP, non-IGP in India, and China

LTE no.	Site	Duration (years)	Annual yield change			Average[a] grain yield (Mg ha^{-1})
			Rate (Mg ha^{-1} per year)	*t*-Statistics	*P*-value	
1	Ludhiana 1	17	−0.113	−5.77	0.00	6.03
2	Ludhiana 2	7	0.163	1.56	0.18	5.31
3	Ludhiana 3	10	0.029	0.29	0.78	5.50
4	Ludhiana 4	12	−0.095	−1.50	0.16	5.74
5	Karnal 1	20	−0.052	−2.79	0.01	6.67
6	Karnal 2	12	−0.047	−0.65	0.53	7.02
7	Pantnagar 1	20	−0.171	−4.37	0.00	6.42
8	Pantnagar 2	23	0.018	0.50	0.62	4.46
9	Pantnagar 3	17	−0.016	−0.56	0.58	4.56
10	Pantnagar 4	15	−0.145	−4.96	0.00	6.45
11	Kanpur	16	0.106	3.10	0.01	4.48
12	Nepalgunj	20	−0.058	−1.13	0.28	3.64
13	Faizabad	15	−0.046	−0.96	0.35	4.17
14	Varanasi	15	0.010	0.33	0.75	4.07
15	Pusa	14	−0.237	−3.52	0.00	3.47
16	Sabour	16	0.012	0.47	0.65	4.06
17	Bhairahwa 1 (early rice)	20	−0.097	−2.84	0.01	2.73
17	Bhairahwa 1 (late rice)	20	0.038	1.64	0.12	3.06
18	Bhairahwa 2	11	−0.107	−2.79	0.02	4.82
19	Parwanipur	20	0.021	0.57	0.58	3.13
20	Tarahara	20	−0.100	−3.07	0.01	3.73
21	Barrackpore	23	−0.022	−0.88	0.39	4.39
22	Kalyani	14	−0.015	−0.48	0.64	3.35
23	Dinajpur (early rice)	9	0.052	0.66	0.53	1.77
23	Dinajpur (late rice)	9	0.011	0.09	0.09	3.37
24	RS Pura	15	0.049	1.24	0.24	4.85
25	Palampur 1	15	−0.033	−0.83	0.42	2.86
26	Palampur 2	12	−0.091	−1.04	0.32	3.12
27	Rewa	23	−0.037	−1.09	0.29	4.08
28	Jabalpur	15	0.058	0.76	0.46	4.96
29	Raipur	11	0.169	2.80	0.02	5.40
30	Navsari	13	0.041	1.27	0.23	3.47
31	Nangong	14	0.048	0.74	0.47	6.80
32	Sichuan (early rice)	10	0.077	0.87	0.41	5.77
32	Sichuan (late rice)	10	−0.067	−0.85	0.42	5.80
33	Jiangsu	12	−0.200	−2.06	0.07	7.34

[a] Average yield for the entire duration of the experiment as given in Table 1.

Least squares linear regression of the magnitude of the yield trend (including the sign) against initial yield in the LTE was performed to test the relationship of the yield trend with initial yields. Initial yield was measured by the average yield in the first 3 years in order to moderate the influence of abnormally high or low yields in the first year of the experiment.

3. Results

3.1. Trends of rice and wheat yields

The annual yield change in rice in 36 data sets from 33 LTE ranged from -0.24 Mg ha^{-1} per year in Pusa to 0.17 Mg ha^{-1} per year in Raipur (-5.1 to 3.6% per

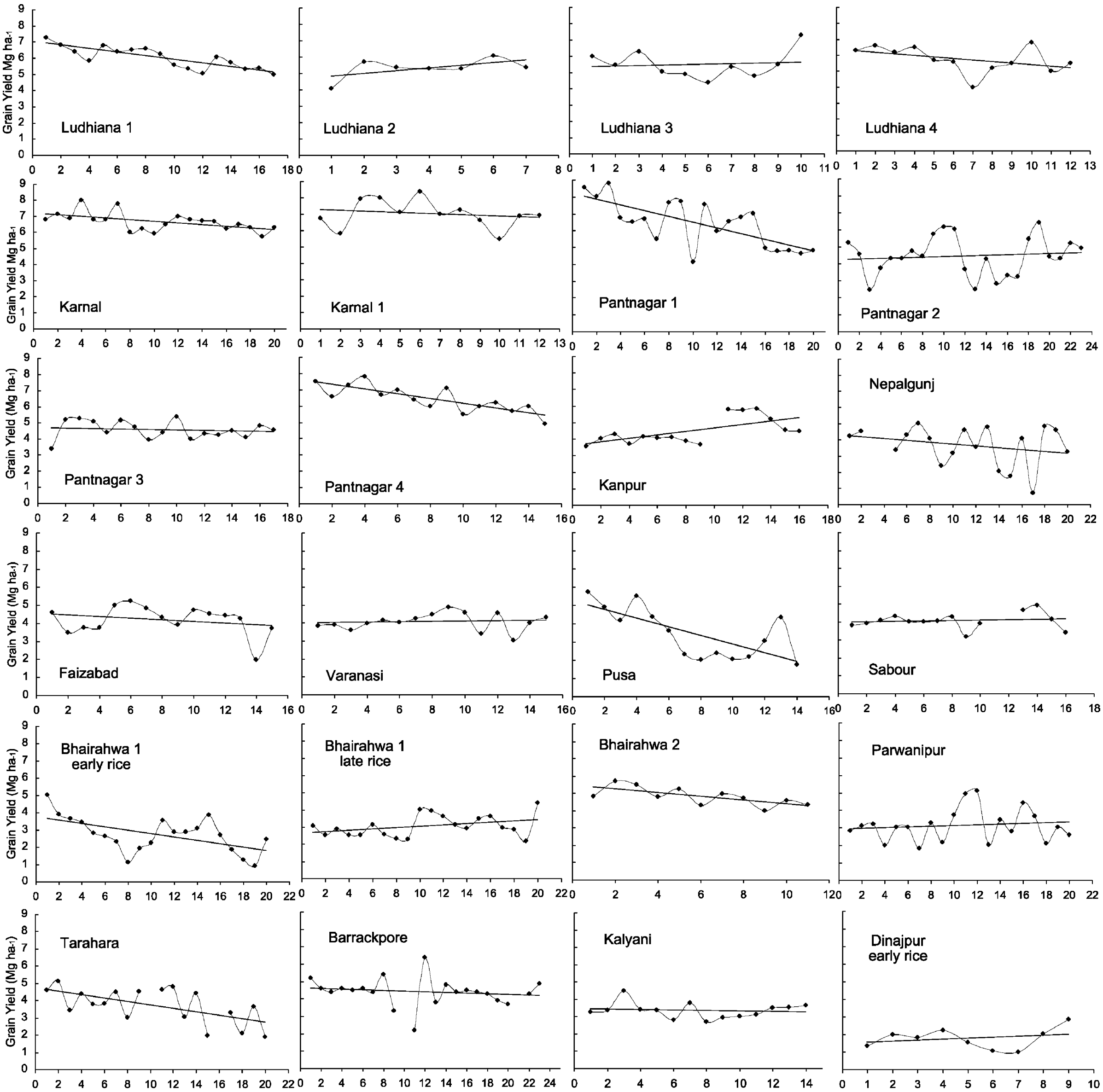

Fig. 2. Grain yield trends of rice in rice–wheat LTEs.

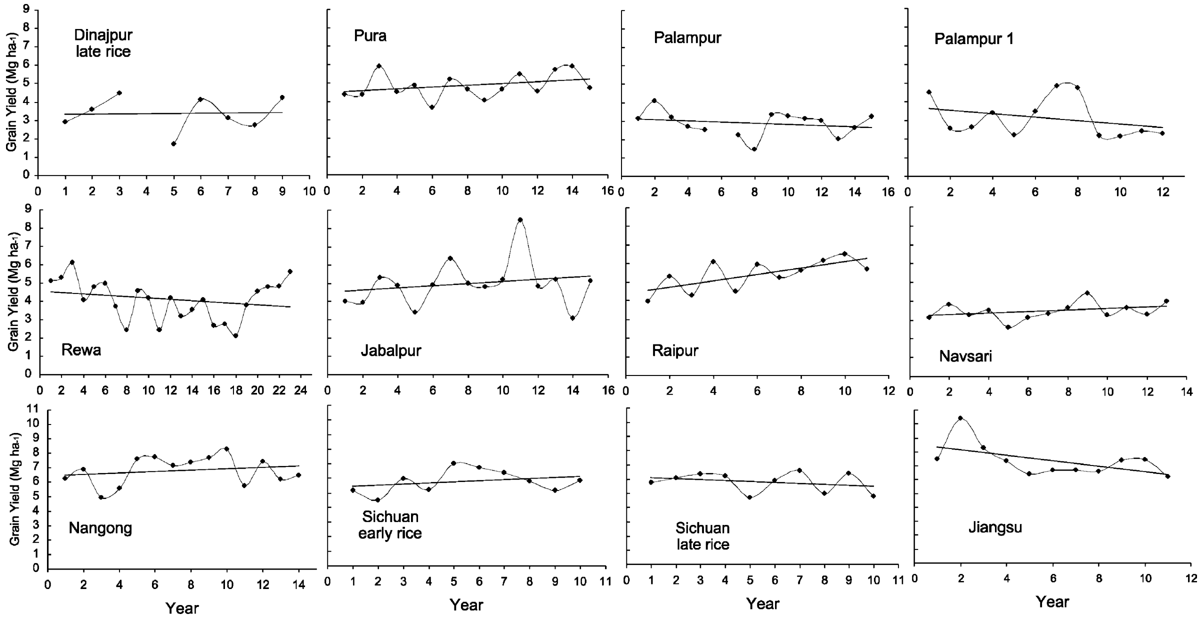

Fig. 2. (*Continued*).

year of the average yield of the respective LTE) after 14 and 11 years of rice–wheat cultivation, respectively (Table 3, Fig. 2). Negative yield trends were observed in 20 of the 36 data sets, 8 of which were significantly different from 0 ($P < 0.05$). These declining trends were observed in areas with average yields ranging from 2.73 Mg ha^{-1} in Bhairahwa to 7.34 Mg ha^{-1} in Jiangsu, indicating that declining yields are not confined to areas with high yield. On the other hand, positive trends were observed in 16 LTE, with significant positive trends in Raipur and Kanpur. At Ludhiana, Karnal and Pantnagar, where rice yields are highest in the IGP, 7 of 10 LTE showed negative yield trends. However, the negative yield trends of only 4 (1 each in Ludhiana and Karnal and 2 in Pantnagar) of these 7 data sets were significantly ($P < 0.05$) different from 0. In Nepal, 3 of the 5 LTE also showed significant declining yield trends.

In wheat, the rate of annual yield change ranged from -0.14 Mg ha^{-1} per year in Navsari to 0.21 Mg ha^{-1} per year in Ludhiana 3 after 13 and 10 years of rice–wheat cultivation, respectively (Table 4, Fig. 3). Of the 33 LTE, 16 showed negative yield trends. Wheat yields appear to be more stable than rice yields, with only 2 LTE (Navsari and Tarahara) showing significant declining trends compared with 8 LTE in rice. Positive trends were observed in 17 LTE, 3 of which (Ludhiana 3, Pantnagar 2 and Palampur 1) were significant.

Across all 33 LTE, a negative average yield trend of -0.023 Mg ha^{-1} per year for rice was obtained. Region-wide averages were also negative for all the transects of the IGP except transect 5 but no significant declining yield trend was observed at sites outside the IGP and China (Table 5). Positive averages were obtained for wheat in all regions except IGP transects 3 and 4 and China (Table 5), with an average yield trend across all LTE of $+0.007$ Mg ha^{-1} per year. On a system (rice + wheat) basis, the average yield trend was -0.019 Mg ha^{-1} per year although statistically significant ($P < 0.05$) declining trends were observed at only six sites in the IGP.

The LTE in China exhibited the highest average system yield at 12.4 Mg ha^{-1} followed by the IGP transect 2 at 10.7 Mg ha^{-1}. However, at the LTE in China, three crops were grown, whereas, at sites in the IGP transect 2, only two crops were grown. It is interesting to note that the rice yields were similar in the IGP 2 and China but wheat yields were higher by about 1.1 Mg ha^{-1} in IGP 2 than in China. Sites in the non-IGP (excluding China) showed the lowest average system yield at 6.8 Mg ha^{-1}.

Table 4
Yield trends of wheat in rice–wheat LTEs in different parts of the IGP, non-IGP in India, and China

LTE no.	Site	Duration (years)	Annual yield change			Average[a] grain yield (Mg ha^{-1})
			Rate (Mg ha^{-1} per year)	t-Statistics	P-value	
1	Ludhiana 1	17	0.019	0.78	0.45	4.62
2	Ludhiana 2	7	0.081	0.75	0.49	4.91
3	Ludhiana 3	10	0.207	4.85	0.00	5.17
4	Ludhiana 4	12	0.065	1.66	0.13	4.38
5	Karnal 1	20	0.008	0.33	0.74	4.68
6	Karnal 2	12	0.151	2.13	0.06	4.45
7	Pantnagar 1	20	0.040	1.26	0.22	4.58
8	Pantnagar 2	23	0.077	3.43	0.00	4.00
9	Pantnagar 3	17	−0.060	−1.58	0.14	3.87
10	Pantnagar 4	15	−0.065	−2.14	0.06	3.33
11	Kanpur	16	−0.020	−1.30	0.22	4.55
12	Nepalgunj	20	0.019	0.59	0.57	2.56
13	Faizabad	15	−0.018	−0.29	0.77	3.42
14	Varanasi	15	−0.029	−0.54	0.60	3.80
15	Pusa	14	−0.071	−1.50	0.16	3.35
16	Sabour	16	0.040	1.61	0.13	3.16
17	Bhairahwa 1	20	−0.045	−1.22	0.24	2.32
18	Bhairahwa 2	11	−0.083	−1.76	0.12	2.10
19	Parwanipur	20	−0.025	−0.89	0.39	1.92
20	Tarahara	20	−0.082	−2.20	0.04	3.20
21	Barrackpore	23	0.002	0.11	0.91	2.96
22	Kalyani	14	0.016	0.56	0.59	2.70
23	Dinajpur	10	0.114	1.94	0.09	3.75
24	RS Pura	15	−0.023	−0.78	0.45	3.29
25	Palampur 1	15	0.124	2.86	0.01	2.70
26	Palampur 2	12	−0.020	−0.51	0.62	2.48
27	Rewa	23	0.060	2.00	0.06	3.14
28	Jabalpur	15	−0.056	−1.30	0.22	2.53
29	Raipur	11	0.052	0.56	0.59	2.77
30	Navsari	13	−0.136	−3.02	0.01	2.20
31	Nangong	14	−0.077	−1.25	0.24	3.00
32	Sichuan	10	−0.063	−1.25	0.25	3.57
33	Jiangsu	12	0.020	0.70	0.50	4.87

[a] Average yield for the entire duration of the experiment as given in Table 1.

Significant declining yield trends in rice were observed in those LTEs, where the average yields were greater than 6 Mg ha^{-1} except in Nangong (Table 3). A significant correlation was also obtained between initial yield and the rate of yield change in rice (Fig. 4). Thus, negative yield trends were associated to some extent with high initial yields. However, both positive and negative yield trends were observed at those sites where average yields were lower (Table 3). For wheat, however, there is no correlation between initial yields and the magnitude of the yield trend.

4. Discussion

The analysis of yield trends of 33 LTE in Bangladesh, China, India and Nepal suggests that significant yield decline is not widespread, however, yields of both rice and wheat are stagnant in 72 and 85% of the LTE, while 22 and 6% of the LTE showed a significant declining yield trend, respectively. On the system basis, 60% of the LTE had a negative yield trend with 18% significant decline. Of the 40% positive trends, 9% were significant. Recently, a similar yield trend analysis of the rice–rice system yields LTE in

Bangladesh, China, India, Indonesia, Malaysia, Philippines and Vietnam was reported (Dawe et al., 2000). Of the 42 data sets, 30 had a downward yield trend. However, only 10 data sets (including 7 from the IRRI experimental farm) were significantly different from 0 ($P < 0.05$).

Data also indicate that in the rice–wheat system, rice yields, particularly in the IGP, declined more rapidly than wheat yields. In contrast to these results, it is often perceived that wheat yields suffer more after rice because of frequent puddling (Sharma and De Datta, 1985). However, it is important to note that the soils in rice–rice and rice–wheat systems differ vastly in texture. The rice–rice soils have a much higher clay content with low bulk density compared with the alluvial rice–wheat soils, which are sandy loam to

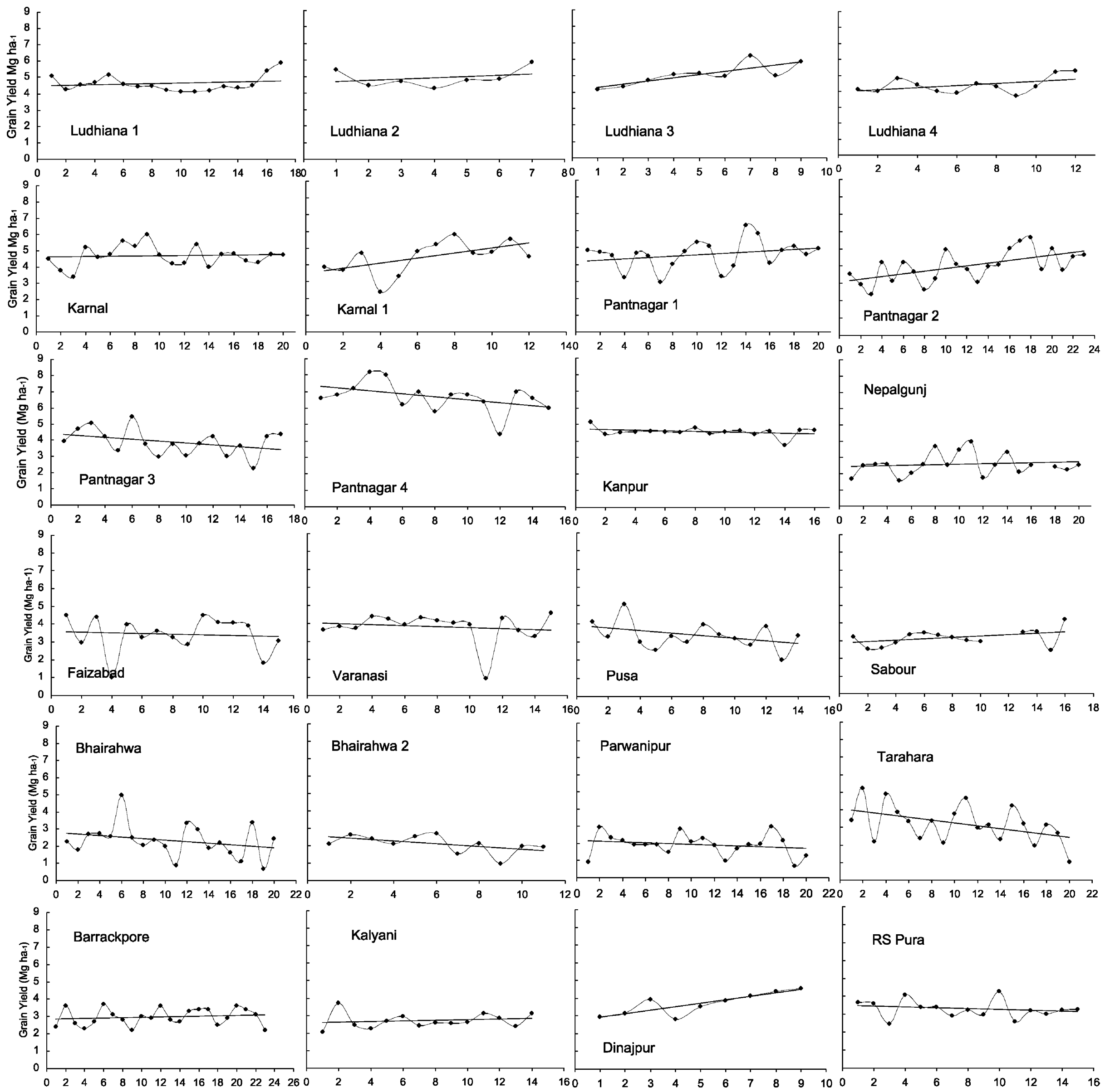

Fig. 3. Grain yield trends of wheat in rice–wheat LTEs.

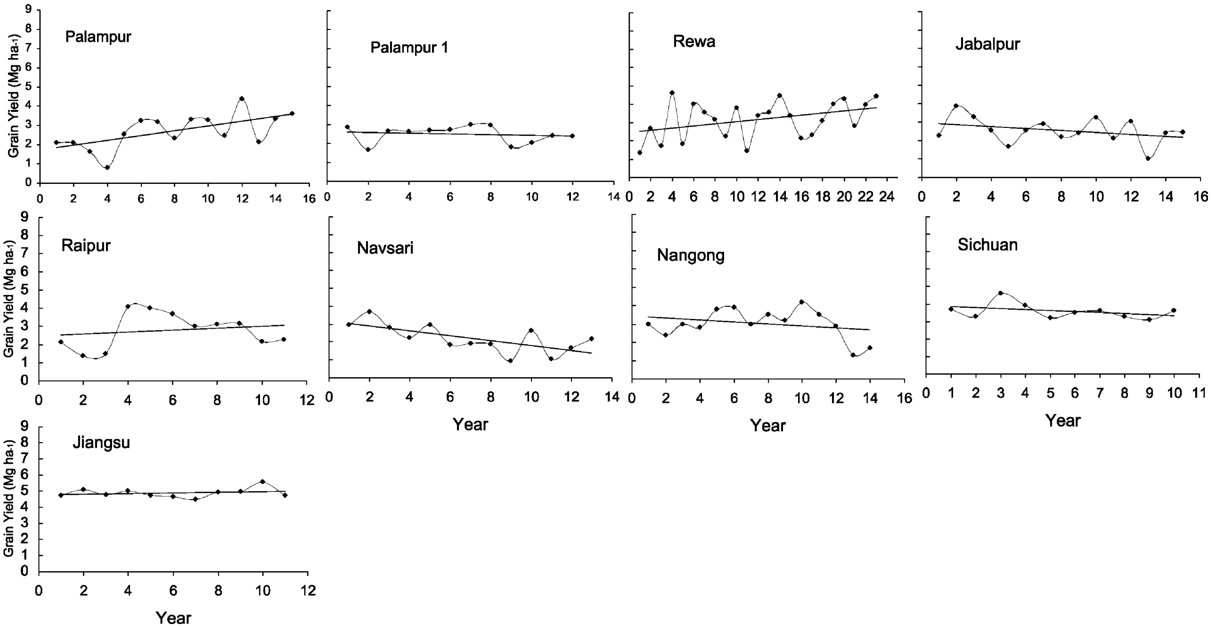

Fig. 3. (*Continued*).

silt loam in texture with high bulk density. We hypothesize that continuous puddling in light-textured soil can result in increased soil compaction, probably because of crystallized ferric oxides, which are cementing agents of soil particles (Talahashi et al., 1999), and subsequent shallow rooting, which in turn can reduce rice yields. Rice, being shallow-rooted and dependent mainly on the nutrients available in the surface 30 cm layer, suffers from nutrient deficiency much earlier than the wheat crop. In addition to its deeper root system, wheat is a longer duration crop than rice and has 30–50 days more to mine soil nutrients to meet its requirements (Chhabra and Thakur, 2000).

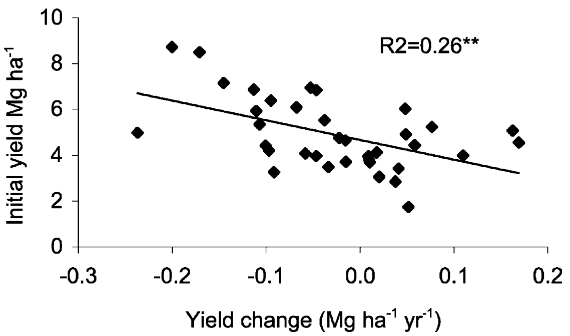

Fig. 4. Relationships of initial yield with the annual yield change in rice.

4.1. Possible causes of yield decline

Out of 33 LTE reviewed, a statistically significant ($P < 0.05$) rice yield decline occurred in eight LTE (Table 3): Ludhiana 1, Karnal 1, Pantnagar 1, Pantnagar 4, Pusa, Bhairahwa 1, Bhairahwa 2 (early rice) and Tarahara. In two LTE (Kanpur and Raipur), however, a statistically significant positive rice yield trend was observed. In contrast, only two LTE (Tarahara and Navsari) showed a significant wheat yield decline, whereas three (Ludhiana 3, Pantnagar 2 and Palampur 1) showed a significant positive yield trend (Table 4). Positive yield trends in rice and wheat in these LTE could be due to the replacing cultivars from year to year with better improved cultivar. Though the existing LTE and available data do not allow us to analyze the improvement in genetic yield potential of newly released cultivars, some other analyses suggest that there has been improvement in the adaptation of new cultivars. For wheat, it is reported that a genetic gain of 1.6% per year has been made in yield since the

Table 5
Yield trends of rice and wheat in rice–wheat LTEs in different parts of the IGP, non-IGP in India, and China

Location	No. of data set	Average yield change (Mg ha^{-1} per year)	Average[a] yield (Mg ha^{-1})	No. of positive and negative trends[b]	
				Positive	Negative
Rice					
IGP2	6	−0.002	6.04	2 (0)	4 (2)
IGP3	6	−0.044	5.00	2 (1)	4 (2)
IGP4	9	−0.056	3.69	4 (0)	5 (4)
IGP5	4	0.007	3.22	2 (0)	2 (0)
Non-IGP	7	0.022	4.11	4 (1)	3 (0)
China	4	−0.036	6.43	2 (0)	2 (0)
Total	36	−0.023	4.63	16 (2)	20 (8)
Wheat					
IGP2	6	0.090	4.70	6 (1)	0
IGP3	6	−0.002	3.82	3 (1)	3 (0)
IGP4	8	−0.036	2.91	1 (0)	7 (1)
IGP5	3	0.044	3.14	3 (0)	0
Non-IGP	7	0.000	2.73	3 (1)	4 (1)
China	3	−0.040	3.82	1 (0)	2 (0)
Total	33	0.007	3.47	17 (3)	16 (2)
System[c]					
IGP2	6	0.070	10.69	3 (1)	3 (1)
IGP3	6	−0.042	8.81	2 (2)	4 (2)
IGP4	8	−0.101	7.06	1 (0)	7 (3)
IGP5	3	0.050	7.39	2 (0)	1 (0)
Non-IGP	7	0.023	6.84	5 (0)	2 (0)
China	3	−0.092	12.39	0	3 (0)
Total	33	−0.019	8.50	13 (3)	20 (6)

[a] Average yield for the entire duration of the experiment as given in Table 1.
[b] Numbers in parentheses indicate the number of LTEs with time trends that are statistically significant at the 5% level.
[c] Rice–rice–wheat systems are included in IGP4, IGP5 and China.

mid-1960s (Morris et al., 1994; Nagarajan, 1998). The improvement was largely due to the higher number of grains per spike and grains per square meter (Sankaran et al., 2000), thereby increasing the harvest index. With rice, whilst yield potential has remained at the same level as for IR8 and Jaya released in the late 1960s, disease and insect resistance and yield stability have improved (Aggarwal et al., 1997; Peng et al., 1999, 2000). More recent cultivars are also better adapted to the biotic and abiotic constraints in intensive rice ecosystems (Peng et al., 2000). Higher genetic improvement in wheat may also partly explain the higher average positive yield trends in wheat than in rice. If this genetic improvement had not occurred, yields of both rice and wheat would probably have had a more extensive and higher magnitude of decline.

Yield decline in an LTE can occur because of a negative change in any of the following factors: soil organic matter and associated nutrient supply, exogenous supply of balanced nutrients, cultivar, climate, insect/disease pressure and crop and soil management. Since all of the LTE were conducted on research farms where crop and soil management, including insect and disease control, was not allowed to change, these factors are probably not the cause of yield decline. Likewise, rice and wheat cultivars were constantly changed during the period of experimentation for better improved cultivars. A yield decline due to changes in the quantity and quality of soil organic

Table 6
Possible causes of yield decline in various LTEs

LTEs	Causes of yield decline
Bhairahwa 1	Delay in sowing (wheat); decline in soil N, available P, K and Zn
Bhairahwa 2	Delay in sowing (wheat); decline in soil C, available P and K
Karnal 1	Decline in soil K
Ludhiana 1	Decrease in solar radiation; increase in minimum temperature, decline in soil C, N, and K
Pantnagar 1	Decline in soil C and N
Pantnagar 4	Decline in soil available P and K
Pusa	Decline in soil K and available Zn
Tarahara	Decline in soil available P and K

matter (SOM) and its impact on nutrient supply and soil structure is also a major concern. We also examined other possible causes of yield decline, i.e. climate change and nutrient imbalances with particular reference to the LTE in which significant yield decline was observed (Table 6).

4.1.1. Decline in soil C

Soil organic matter serves as a soil conditioner, nutrient source and substrate for microbial activity (Schnitzer, 1991). Continuous cropping, removal of crop residues and excessive tillage are believed to result in a decrease in soil C, which may cause yield declines. In the present study, total soil C declined with continuous cultivation in the Bhairahwa 1 and Ludhiana 1 LTE (Ladha et al., in press). Timsina et al. (1997) used simulation model to analyze an LTE at Pantnagar, one of the 33 LTEs presented here, and reported that yield decline in rice was due to decline in SOC and total N. In the major rice–wheat regions of northwestern India, soil C has decreased from 0.5% in the 1960s to 0.2% in the late 1990s (Sinha et al., 1998). Such a decline in SOM is prevalent throughout rice–wheat systems in India (Nambiar, 1994), while soil C is conserved or even increases in intensive double- and triple-crop irrigated rice systems in the lowland tropics with high temperatures and adequate soil moisture throughout the year (Cheng, 1984; Dobermann and Witt, 2000).

However, increasing stocks of SOM do not necessarily maintain or increase yield. For instance, SOM content increased in the Tarahara LTE but yields of both rice and wheat declined (Yadav et al., 1999). Similarly, in the Bhairahwa 1 LTE, the continuous addition of FYM increased SOM but yields declined (Regmi et al., 2002a). This data suggests that SOM and crop productivity are not intimately linked (Ladha et al., in press). Bronson et al. (1998) have argued that the total size of SOM stocks is not as important as the size of the active fraction that is directly involved in nutrient availability. There is a great need to fully quantify the role of SOM in relation to crop productivity and sustainability in rice–wheat systems.

4.1.2. Nutrient depletion and imbalances

4.1.2.1. Depletion of soil N. A gradual decline in soil N supply, N uptake efficiency, and fertilizer N-use efficiency has been identified as a possible reason for yield decline in rice–rice systems (Cassman et al., 1995; Dawe et al., 2000; Dobermann et al., 2000). These factors, either individually or in combination, may be responsible for a yield decline in the rice–wheat system as well. The soil N data suggested that there was a gradual depletion of soil N together with a decline in plant available N in the Ludhiana 1 (Bhandari et al., 2002), Pantnagar 1 (Ram, 2000) and Bhairahwa 1 (Regmi et al., 2002a) LTE. In Ludhiana 1, total soil N declined at 0.03 g kg^{-1} per year in treatments with NPK. Apparent N balance estimates in the Bhairahwa 1 LTE showed a net outflux of N (Regmi et al., 2002a). A similar negative N balance was also estimated in the Bhairahwa 2 (data not shown). Apart from lower N input, poor N management also seemed to be a major problem in these LTE. For example, in the Bhairahwa 1 and Bhairahwa 2 LTE, N was applied in only two splits (50% at transplanting and the remaining 50% topdressed at 25–30 days after transplanting rice). Moreover, in other experiments where N was applied in 3 splits, the addition was not demand-based. To achieve high yields, the timing of N application is important, particularly in sandy rice–wheat soils with high pH, in which N losses by leaching and volatilization are high (Singh et al., 1991; Bhandari et al., 2002). We suggest that application of N should be based on crop demands using tools such as the chlorophyll (SPAD) meter or leaf color chart (LCC) for increasing yield, N-use efficiency and productivity (Balasubramanian et al., 1999).

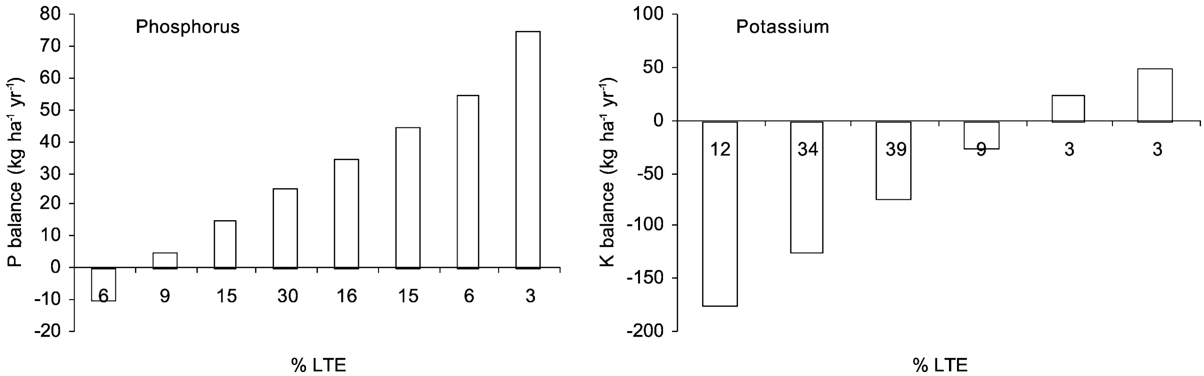

Fig. 5. Apparent P and K balances in LTEs in Asia.

4.1.2.2. Reduced soil P availability. The apparent P balance estimates showed that the recommended rates of P either equaled or exceeded P removal (Fig. 5). Only two (Ludhiana 4 and Parwanipur) of the 33 LTE had a negative P balance. The P balance estimates were consistent with the changes in soil P status in the Ludhiana 1 (Bhandari et al., 2002), Bhairahwa 1 (Regmi et al., 2002a) and Bhairahwa 2 (Regmi et al., 2002b) LTE. Therefore, total soil P was not limiting. However, unfavorable soil conditions can reduce its bio-availability and contribute to yield decline (Sanyal and De Datta, 1991). For example, in Bhairahwa 1, inadequate P availability was a reason for yield decline in early rice but the second rice crop escaped P deficiency (Regmi et al., 2002a). The differential availability of P to the crops could be due to changes in the oxidation–reduction status of soil resulting from continuous submergence in late rice, intermittent wetting and drying in early rice and aerobic conditions during wheat. Reduced soil conditions result in increased P availability because of reduction of ferric iron phosphate compounds and increased solubility of Ca–P compounds due to pH decrease in alkaline soils (Kirk et al., 1990; Sanyal and De Datta, 1991). Differences in P availability were also possible because of increased P sorption during the drying phase (Brandon and Mikkelsen, 1979; Sah and Mikkelsen, 1986) and differences in soil P diffusion in submerged and dry soils (Turner and Gilliam, 1976). Thus, Gami et al. (2001) and Regmi et al. (2002a) suggested that proper water management is crucial in increasing fertilizer P-use efficiency. Dawe et al. (2000) observed a decline in Olsen P in the Pantnagar 4 LTE and mentioned it as a cause of yield decline.

4.1.2.3. Depletion of soil K. In over 90% of the LTE, the fertilizer K additions were not sufficient to sustain a neutral K input–output balance (Fig. 5). All the LTE with significant yield decline had large negative balances of K. The K balances were consistent with the changes in soil K status in the Ludhiana 1 and Bhairahwa 1 LTE. In these two LTE, soil K declined by 62 and 33%, respectively, after 10 years of cultivation (Bhandari et al., 2002; Regmi et al., 2002a). In another LTE (Bhairahwa 2), a large response to K and reversal of the yield decline of rice and wheat were observed when additional K was applied to the main LTE plots (Regmi et al., 2002b). Similar observations were made by Dawe et al. (2000), Duxbury et al. (2000) and Yadav et al. (2000b) in rice–wheat systems. Regmi et al. (2002b) also reported K deficiency enhancing the incidence of *Helminthosporium* leaf blight and yield losses of wheat. We suggest that the present rate of K application is inadequate and higher amounts of K application in all LTE are needed to increase the yields of both rice and wheat. We argue that the perception of K as rarely being a yield-limiting factor because most soils of the alluvial floodplains of Asia are high in K, and additional K is supplied from irrigation water (De Datta and Mikkelsen, 1985; Bajwa, 1994), needs to be reviewed. Moreover, farmers should be encouraged to incorporate straw, which would help replenish K to some extent, rather than burn or remove it. However, as many farmers practice mixed farming, incorporation of straw may not be practicable until a suitable alternative is identified for animal feed.

4.1.2.4. Depletion of S and micronutrients. Deficiency of S and micronutrients could also be a cause of yield decline as reports exist of isolated micronutrient deficiencies in the IGP, particularly where the soils are calcareous (Duxbury et al., 2000). A declining trend in available Zn content of soils causing a significant decline in the yield of rice and wheat at recommended levels of NPK was reported from the IGP of India (Nambiar and Abrol, 1989). The significant yield decline in the Pusa LTE in the present analysis was arrested when Zn was applied along with NPK (Sakal, 2000). The more stable yield with the FYM treatment compared with the NPK treatment, could partially be ascribed to the supply of micro- and secondary nutrients with FYM (Ladha et al., in press; Regmi et al., 2002b). However, it should be noted that measurements of micro- and secondary nutrients in soil and plants were undertaken in only a limited number of LTE, making it difficult to identify their deficiency as a cause of yield decline. Indirect evidence, however, suggests that deficiency of such elements was not widespread. A majority of the LTE used single superphosphate as a source of P in the NPK treatment; therefore, the deficiency of S can be ruled out as the cause of yield decline because single superphosphate contains considerable amounts of S. In some of these LTE, blanket applications of micronutrients were made either once in three years or whenever the apparent deficiency symptoms appeared. Detailed soil and plant analyses will be required to further evaluate the role of these nutrients in yield stability.

4.1.2.5. Soil salinity and other changes in soil properties. Soil salinity is also perceived as a cause of yield decline in the rice–wheat system of the IGP, particularly in transects 1 and 2. As the soils of these regions are generally highly porous and light- to medium-textured, frequent irrigation is needed. In many locations, IGP2 for example, groundwater accounts for 60–65% of the total irrigation requirement (Singh, 2000). In Haryana, India, the rice–wheat growing areas in Ambala, Kaithal, Karnal, Kurukshetra, Panipat and Yamunanagar districts show a water table decline (Singh, 2000). In Punjab, India, a 2–5 m decline in the water table has been recorded from 1984 to 1994 (Sinha et al., 1998). The farmers in the upper transects of the IGP now use poor-quality groundwater and run a risk of increasing soil salinity (Sinha et al., 1998). However, in the LTE reviewed in this paper, either surface water or good-quality groundwater was used for irrigation and hence salinity may be discounted as a reason for yield decline.

Changes in soil physical properties, hard-pan formations and the accumulation of toxic substances have not been studied, therefore, it is difficult to judge their role in yield decline.

4.1.3. Delay in planting

A delay in sowing of wheat results in yield loss because of the rise in temperature during grain filling (Penning de Vries, 1993; Matsui et al., 1997). At Bhairahwa 1, wheat yield declined because of a gradual delay in sowing (Regmi et al., 2002a). This yield loss was estimated to be 0.04 Mg ha^{-1} per day of delay. When actual yields were adjusted for the yield reduction caused by a delay in sowing, there was no yield decline. Hobbs and Morris (1996) reported a yield decrease of 1% for every day's delay in sowing wheat beyond the optimum sowing date (15–20 November) in South Asia. Regmi et al. (2002a) simulated the effect of planting date on yield of wheat using the CERES model and observed that sowing of wheat after the third week of November would lower the yield. In most rice–wheat areas, late planting is a major problem (Hobbs and Gupta, 2002). Late planting not only reduces yield but also reduces the use efficiency of inputs applied to the wheat crop. The reasons for late planting of wheat in the rice–wheat system include late harvest of the preceding rice crop; growing of long-duration, photosensitive, high-quality basmati rice that matures late; a long turnaround time between rice harvest and wheat planting; and growing of a short-duration third crop after rice. Measures to avoid late planting include practicing zero tillage in wheat and direct seeding of rice and have been discussed in more detail by Gupta et al. (in press) and Hobbs and Gupta (2002).

4.1.4. Climate change

There is a widespread concern over possible climatic changes caused by increase in the concentration of greenhouse gases in the atmosphere (Watson et al., 1996). Analyses of weather parameters for Ludhiana, Karnal, Delhi, Varanasi, 24-Pargana, Raipur and Pantnagar located in and outside the IGP showed that solar radiation decreased over the years and in Ludhiana and Karnal, the decrease was significant (Pathak et al., 2002b). Average minimum temperature also increased in several places in the IGP and in Ludhiana the increase was significant. Kukla and Karl (1993) analyzed data from several countries covering 50% of the land in the Northern Hemisphere and 10% of land in the Southern Hemisphere. There was a general rise in minimum temperature all over the globe with the exception of the eastern coast of North America where it decreased. Maximum temperature showed no specific trend. The decrease in radiation and increase in minimum temperature lowered rice yields probably due to decreased photosynthesis, increased respiration, and shortened vegetative and grain-filling period (Yoshida and Parao, 1976; Penning de Vries, 1993; Horie et al., 1995). It is widely perceived that in all major cities of India aerosol and particulate matter concentration has been increasing, resulting in decreased solar radiation and consequently increased minimum temperature (Aggarwal et al., 2000b). This would limit the amount of light reaching the plant to higher red wavelengths that are less photosynthetically active therefore resulting in lower yields. However, whether these weather changes are only confined to urban areas needs verification.

5. Conclusions

The analysis of yield trends of LTE in Bangladesh, China, India and Nepal suggest that although significant yield decline is not widespread, yields of both rice and wheat are stagnant. In the rice–wheat system, particularly in the IGP, rice yields are declining more rapidly then wheat. Rice yield declined significantly in 8 of 36 data sets and in wheat 2 of 33 data sets had significant decline. On a system (rice + wheat) basis, the significant declining trends were observed at only six sites in the IGP. The causes of yield decline are mostly location specific but depletion of soil K seems to be most common. Depletion of soil C, N, Zn, reduced availability of P, decreases in solar radiation and increases in minimum temperature are the other potential causes of yield decline.

There is an urgent need to develop and implement strict guidelines to ensure better management of LTE. The lack of historical soil and plant samples is potentially a major problem for identifying the specific cause of yield decline. Therefore, more detailed data collection and archives of soil/plant samples should be maintained to unravel the cause–effect relationship. A few LTE should be selected for continued support with appropriate changes in crop and nutrient management aimed at increasing yields to potential attainable yields. The issue of climate change and the effect of pollution on productivity need more attention. It would be useful to extract historical data on radiation and the effect of air quality on photosynthetic efficiency for different regions. At the same time, investment is needed in equipment for collecting accurate climatic data.

Acknowledgements

The authors acknowledge the help received from the following persons in preparing the manuscript: Dr. R.K. Sahu, Indira Gandhi Agricultural University, Raipur, Chhatishgarh, India; Dr. A.S.R.A.S. Sastri, Indira Gandhi Agricultural University, Raipur, Chhatishgarh, India; Dr. Zheng Jiaguo, Sichuan Academy of Agricultural Sciences, China; Dr. Zhuang Hengyang, Agricultural College, Yangzhou University, China; Dr. P.K. Aggarwal, Indian Agricultural Research Institute, New Delhi, India; Mr. Sushil Chaudhary, Rice–Wheat Consortium for Indo-Gangetic Plains, IARI Campus, New Delhi, India; Craig Meisner, CIMMYT, Bangladesh; U. Singh, International Fertilizer Development Center, USA; Dr. D.K. Das, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal, India. We thank Dr. A. Ismail and Dr. T. Nozoe for their constructive comments on the manuscript.

References

Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K., 2000. Long-term soil fertility experiments in rice–wheat cropping systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, 171 pp.

Aggarwal, P.K., Kropff, M.J., Cassman, K.G., ten Berge, H.F.M., 1997. Simulating genotypic strategies for increased rice yield potential in irrigated, tropical environments. Field Crops Res. 51, 5–17.

Aggarwal, P.K., Bandyopadhyay, S.K., Pathak, H., Kalra, N., Chander, S., Sujith Kumar, S., 2000a. Analyses of yield trends of the rice–wheat system in north-western India. Outlook Agric. 29, 259–268.

Aggarwal, P.K., Talukdar, K.K., Mall, R.K., 2000b. Potential yields of rice–wheat system in the Indo-Gangetic Plains of India. Rice–Wheat Consortium Paper Series 10. Rice–Wheat Consortium for the Indo-Gangetic Plains, and Indian Agricultural Research Institute, New Delhi, India, 11 pp.

Badaruddin, M., Razzaque, M.A., Meisner, C.A., Razu, R.A., 2000. Long-term nutrient management for sustaining rice and wheat yields in rice–wheat systems. In: Abrol, I.P., Bronson, K., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, and Indian Agricultural Research Institute, New Delhi, India, pp. 56–62.

Bajwa, M.I., 1994. Soil K status, K fertilizer usage and recommendations in Pakistan. Potash Review No. 3/1994. Subject 1, 20th Suite, Basel. International Potash Institute, 67 pp.

Balasubramanian, V., Morales, A.C., Cruz, R.T., Abdulrachman, S., 1999. On-farm adaptation of knowledge-intensive nitrogen management technologies for rice systems. Nutr. Cycl. Agroecosyst. 53, 59–69.

Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D., Gupta, R.K., 2002. Trends of yield and soil nutrient status in a long-term rice–wheat experiment in the Indo-Gangetic Plains of India. Soil Sci. Soc. Am. J. 66, 162–170.

Bhattarai, E.M., Mishra, R., 1999. Effect of long-term application of chemical fertilizer and manure on crop productivity and soil fertility under rice–wheat cropping pattern at Khajura, Nepalgunj. In: Proceedings of the First National Workshop on Long-term Soil Fertility Experiments, Khumaltar, Lalitpur, Nepal, August 11–13, 1998, pp. 59–84.

Brandon, D.M., Mikkelsen, D.S., 1979. Phosphorus transformations in alternately flooded Californian soils. I. Cause of plant phosphorus deficiency in rice rotation crops and correction methods. Soil Sci. Soc. Am. J. 43, 989–994.

Bronson, K.F., Cassman, K.G., Wassmann, R., Olk, D.C., van Noordwijk, M., Garrity, D.P., 1998. Soil carbon dynamics in different cropping systems in principal ecoregions of Asia. In: Lal, R., Kimble, J., Follet, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 35–57.

Byerlee, D., Siddiq, A.K., 1994. Has the green revolution been sustained: the quantitative impacts of the seed-fertilizer technology in Pakistan revisited. World Dev. 22, 1345–1361.

Byerlee, D., Ali, M., Siddiq, A., 2002. Sustainability of the rice–wheat systems in Pakistan's Punjab: how big is the problem? In: Ladha, J.K., James, E.H., Duxbury, J.D., Gupta, R.K., Buresh, R.J. (Eds.), Improving the Productivity and Sustainability of Rice–Wheat Systems: Issues and Impact. ASA Special Publication. ASA, Madison, WI.

Cassman, K.G., De Datta, S.K., Olk, D.C., Alcantara, J., Samson, M., Descalsota, J.P., Dizon, M., 1995. Yield decline and the nitrogen economy of long-term experiments on continuous irrigated rice systems in Asia. In: Lal, R., Stewart, B.A. (Eds.), Soil Management: Experimental Basis for Sustainability and Environmental Quality. CRC Press, Boca Raton, FL, pp. 181–222.

Cheng, Y.-S., 1984. Effects of drainage on the characteristics of paddy soils in China. In: Organic Matter and Rice. International Rice Research Institute, Los Baños, Philippines, pp. 417–430.

Chhabra, R., Thakur, N.P., 2000. Long-term study on phosphorus fertilization for rice–wheat cropping system in alkali soils in the Indo-Gangetic Plains. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, and Indian Agricultural Research Institute, New Delhi, India, pp. 31–39.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S., Zhen, Q.X., 2000. How widespread are yield declines in long-term rice experiments in Asia? Field Crops Res. 66, 175–193.

De Datta, S.K., Mikkelsen, D.S., 1985. Potassium nutrition of rice. In: Munson, R.D., Summer, M.E., Bishop, W.D. (Eds.), Potassium in Agriculture. ASA, CSSA, SSSA, Madison, WI, pp. 665–699.

Dobermann, A., Witt, C., 2000. The potential impact of crop intensification on carbon and nitrogen cycling in intensive rice systems. In: Kirk, G.J.D., Olk, D.C. (Eds.), Carbon and Nitrogen Dynamics in Flooded Soils. International Rice Research Institute, Philippines, pp. 1–25.

Dobermann, A., Dawe, D., Roetter, R.R., Cassman, K.G., 2000. The reversal of the yield decline in IRRI's long-term continuous cropping experiment. Agron. J. 92, 633–643.

Duxbury, J.M., Abrol, I.P., Gupta, R.K., Bronson, K., 2000. Analysis of long-term soil fertility experiments with rice–wheat rotation in South Asia. In: Abrol, I.P., Bronson, K., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. vii–xxii.

Gami, S.K., Ladha, J.K., Pathak, H., Shah, M.P., Pasuquin, E., Pandey, S.P., Hobbs, P.R., Joshy, D., Mishra, R., 2001. Long-term changes in yield and soil fertility status in a twenty-year in a 20-year rice–wheat experiment in Nepal. Biol. Fert. Soils 34, 73–78.

Gangwar, B., Kumar, A. (Eds.), 1998. Annual Report—1997–1998. All India Coordinated Research Project on Cropping Systems Research (AICRP-CSR), PDCSR, Modipuram, 268 pp.

Gupta, R.K., Naresh, R.K., Hobbs, P.R., Jiaguo, J., Ladha, J.K., in press. Sustainability of post-green revolution agriculture: the rice–wheat cropping system of the Indo-Gangetic plains and China. In: Ladha, J.K., James, E.H., Duxbury, J.D., Gupta, R.K., Buresh, R.J. (Eds.), Improving the Productivity and Sustainability of Rice–Wheat Systems: Issues and Impact. ASA Special Publication. ASA, Madison, WI.

Hobbs, P.R., Gupta, R.K., 2002. Resource conserving technologies for wheat in rice–wheat systems. In: Ladha, J.K., James, E.H., Duxbury, J.D., Gupta, R.K., Buresh, R.J. (Eds.), Improving the

Productivity and Sustainability of Rice–Wheat Systems: Issues and Impact. ASA Special Publication. ASA, Madison, WI.

Hobbs, P.R., Morris, M.L., 1996. Meeting South Asia's future food requirements from rice–wheat cropping systems: priority issues facing researchers in the post green revolution era. NRG Paper 96-01. CIMMYT, Mexico, D.F., pp. 1–45.

Horie, T., Nakagawa, H., Ceneno, H.G.S., Kropff, M.J., 1995. The rice crop simulation model SIMRIW and its testing. In: Matthews, R.B., Kropff, M.J., Bachelet, D., van Laar, H.H. (Eds.), Modelling the Impact of Climate Change on Rice Production in Asia. CAB International and International Rice Research Institute, Philippines, pp. 51–66.

Kirk, G.J.D., Yu, T.R., Chaoudhary, F.A., 1990. Phosphorus chemistry in relation to water regime. Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. International Rice Research Institute, Manila, Philippines, pp. 211–223.

Knudsen, D., Peterson, G.A., Pratt, P.F., 1982. Lithium, sodium, and potassium. In: Page, A.L. (Ed.), Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, 2nd ed. Agronomy No. 9. ASA, SSSA, Madison, WI, pp. 225–246.

Kukla, G., Karl, T.R., 1993. Nighttime warming and greenhouse effect. Environ. Sci. Technol. 27, 1469–1474.

Ladha, J.K., Fischer, K.S., Hossain, M., Hobbs, P.R., Hardy, B (Eds.), 2000. Improving the productivity and sustainability of rice–wheat systems of the Indo-Gangetic Plains: a synthesis of NARS-IRRI partnership research. IRRI Discussion Paper No. 40, 31 pp.

Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D., Gupta, R.K., in press. Productivity trends in intensive rice–wheat cropping systems in Asia. In: Ladha, J.K., James, E.H., Duxbury, J.D., Gupta, R.K., Buresh, R.J. (Eds.), Improving the Productivity and Sustainability of Rice–Wheat Systems: Issues and Impact. ASA Special Publication. ASA, Madison, WI.

Lin, B., Li, J., 1992. Some results of long-term trials in sustainable rice farming in China. In: Proceedings of the International Symposium on Paddy Soils. Chinese Academy Agricultural Sciences, Nanjing, pp. 274–280.

Matsui, T., Namuco, O.S., Ziska, J.H., Horie, T., 1997. Effects of high temperature and CO_2 concentration on spikelet sterility in Indica rice. Field Crops Res. 51, 213–219.

Morris, M.L., Dubin, H.J., Pokhrel, T., 1994. Returns to wheat breeding research in Nepal. Agric. Econ. 10, 269–282.

Nagarajan, S., 1998. Perspectives on wheat demand and research needs. In: Nagarajan, S., Singh, S., Tyagi, B.S. (Eds.), Wheat Research Needs Beyond 2000 AD. Narosa, New Delhi, pp. 1–12.

Nambiar, K.K.M., 1994. Soil Fertility and Crop Productivity under Long-term Fertilizer use in India. Indian Council for Agricultural Research, New Delhi, India, pp. 27–28.

Nambiar, K.K.M., Abrol, I.P., 1989. Long-term fertilizer experiments in India: an overview. Fertil. News 34, 11–20.

Narang, R.S., Virmani, S.M., 2001. Rice–wheat cropping systems of the Indo-Gangetic Plains of India. Rice–Wheat Consortium Paper Series 11. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, and International Crops Research Institute for the Semi-arid Tropics, Patancheru, Andhra Pradesh, India, 36 pp.

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939.

Pathak, H., Aggarwal, P.K., Roetter, R., Kalra, N., Bandyopadhaya, S.K., Prasad, S., Van Keulen, H., 2002a. Modelling the quantitative evaluation of soil nutrient supply, nutrient use efficiency, and fertilizer requirements of wheat in India. Nutr. Cycl. Agroecosyst., in press.

Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Yadvinder, Singh, B., Kamra, S.K., Mishra, B., Sastri, A.S.R.A.S., Aggarwal, H.P., Das, D.K., Gupta, R.K. (2002b). Climatic potential and on-farm yield trends of rice and wheat in the Indo-Gangetic Plains. Field Crops Res., in press.

Peng, S., Cassman, K.G., Virmani, S.S., Sheehy, J., Khush, G.S., 1999. Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential. Crop Sci. 39, 1552–1559.

Peng, S., Laza, R.C., Visperas, R.M., Sanico, A.L., Cassman, K.G., Khush, G.S., 2000. Grain yield of rice cultivars and lines developed in the Philippines since 1966. Crop Sci. 40, 307–314.

Penning de Vries, F.W.T., 1993. Rice production and climate change. In: Teng, P.S., Penning de Vries, F.W.T. (Eds.), Systems Approaches for Agricultural Development. Kluwer Academic Publishers, Netherlands, pp. 175–189.

Powlson, D.S., Pruden, G., Johnston, A.E., Jenkinson, D.S., 1986. The nitrogen cycle in Broadbalk wheat experiment—recovery and losses of ^{15}N-labelled fertility applied in springs and inputs of N from the atmosphere. J. Agric. Sci. Camb. 107, 591–609.

Ram, N., 2000. Long-term effects of fertilizers on rice–wheat–cowpea productivity and soil properties in Mollisols. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 50–55.

Regmi, A.P., Ladha, J.K., Pathak, H., Pasuquin, E., Dawe, D., Hobbs, P.R., Joshy, D., Maskey, S.L., Pandey, S.P., 2002a. Analyses of yield and soil fertility trends in a 20-year rice–wheat experiment in Nepal. Soil Sci. Soc. Am. J. 66, 857–867.

Regmi, A.P., Ladha, J.K., Pasuquin, E., Pathak, H., Hobbs, P.R., Shrestha, L.L., Gharti, D.B., Duveiller, E., 2002b. The role of potassium in sustaining yields in a long-term rice–wheat experiment in the Indo-Gangetic Plains of Nepal. Biol. Fertil. Soils 36, 240–247.

Sah, R.N., Mikkelsen, D.S., 1986. Transformation of inorganic phosphorus during the flooding and raining cycles of soils. I. Cause of plant phosphorus deficiency in rice rotation crops and correction methods. Soil Sci. Soc. Am. J. 50, 62–67.

Saha, M.N., Saha, A.R., Mandal, B.C., Ray, P.K., 2000. Effects of long-term jute–rice–wheat cropping system on crop yields and soil fertility. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 94–104.

Sakal, R., 2000. Long-term effects of nitrogen phosphorous, and zinc management on crop yields and micronutrient availability in rice–wheat cropping system in calcareous soils. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 73–82.

Sankaran, V.M., Aggarwal, P.K., Sinha, S.K., 2000. Improvement in wheat yields in northern India since 1965: measured and simulated trends. Field Crops Res. 66, 141–149.

Sanyal, S.K., De Datta, S.K., 1991. Chemistry of phosphorus transformations in soil. Adv. Soil Sci. 16, 1–120.

SAS, 1995. SAS System for Windows^{TM}, Release 6.11. SAS Institute, Cary, NC.

Schnitzer, M., 1991. Soil organic matter—the next 75 years. Soil Sci. 151, 41–58.

Sharma, P.K., De Datta, S.K., 1985. Physical properties and processes of puddled rice soils. Adv. Soil Sci. 5, 139–178.

Sharma, P.K., Ladha, J.K., Verma, T.S., Bhagat, R.M., Padre, A.T., in press. Long-term effects of lantana (*Lantana* spp.) biomass on crop yields and nutrient status in a rice–wheat cropping system. Biol. Fertil. Soil.

Singh, R.B., 2000. Environmental consequences of agricultural development: a case study from the Green Revolution state of Haryana. Agric. Ecosyst. Environ. 82, 97–103.

Singh, P., Khan, R.A., 2000. Long-term effects of fertilizer practices on yield and profitability of rice–wheat cropping system. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 7–13.

Singh, K.N., Swarup, A., 2000. Effect of long-term rice–wheat cropping sequence on yield and soil properties in reclaimed sodic soils. In: Abrol, I.P., Bronson, K., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 40–49.

Singh, B., Singh, Yadvinder, Khind, C.S., Meelu, O.P., 1991. Leaching losses of urea-N applied to permeable soils under lowland rice. Fert. Res. 28, 179–184.

Singh, B., Singh, Yadvinder, Khind C.S., Meelu, O.P., 2000. Phosphorus management for sustained crop production in rice–wheat cropping system in northwest India. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, and Indian Agricultural Research Institute, New Delhi, India, pp. 22–30.

Singh, Y., Singh, S.P., Bhardwaj, A.K., 2000. Long-term effects of nitrogen, phosphorus, and potassium fertilizers on rice–wheat productivity and properties of mollisols in Himalayan foothills. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 14–21.

Singh, Yadvinder, Singh, B., Meelu, O.P., Khind, C.S., 2000. Long-term effects of organic manuring and crop residues on the productivity and sustainability of rice–wheat cropping system in Northwest India. In: Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K. (Eds.), Long-term Soil Fertility Experiments in Rice–Wheat Cropping Systems. Rice–Wheat Consortium Research Series 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp. 149–162.

Sinha, S.K., Singh, G.B., Rai, M., 1998. Decline in crop productivity in Haryana and Punjab: myth or reality? Indian Council of Agricultural Research, New Delhi, India, 89 pp.

Smaling, E.M.A., Fresco, L.O., 1993. A decision support model for monitoring nutrient balances under agricultural land use, NUTMON. Geoderma 60, 235–256.

Talahashi, T., Park, C.Y., Nakajima, H., Sekiya, H., Toriyama, K., 1999. Ferric iron transformation in soils with rotation of irrigated rice–upland crops and effect on soil tillage properties. Soil Sci. Plant Nutr. 45, 163–173.

Timsina, J., Connor, D.J., 2001. Productivity and management of rice–wheat cropping systems: issues and challenges. Field Crops Res. 69, 93–132.

Timsina, J., Singh, U., Singh, Y., 1997. Addressing sustainability of rice–wheat systems: analysis of long-term experimentation and simulation. In: Kropff, M.J., Teng, P.S., Aggarwal, P.K., Bouma, J., Bouman, B.A.M., Jones, J.W., van Laar, H.H. (Eds.), Applications of Systems Approaches at the Field Level. Kluwer Academic Publishers, Dordrecht, pp. 383–397.

Turner, F.T., Gilliam, J.W., 1976. Increased P diffusion as an explanation of increased P availability in flooded rice soils. Plant Soil 45, 365–377.

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.

Watson, R.T., Zinyowera, M.C., Moss, R.H., Dokken, D.J., 1996. Climate change 1995, impacts, adaptations and mitigation of climate change: scientific-technical analyses. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, USA, p. 879.

Witt, C., Dobermann, A., Abdulrachman, S., Gines, H.C., Guanghuo, W., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Van Tiem, L., Simbahan, G., Olk, D.C., 1999. Internal nutrient efficiencies in irrigated lowland rice of tropical and subtropical Asia. Field Crops Res. 63, 113–138.

Yadav, C.R., Bhujel, R.B., Prasai, H.K., Chaudhary, A.L., 1999. Long-term fertility trial on rice–wheat–fallow cropping system at Tarahara. In: Long-term Soil Fertility Experiments. Proceedings of the First National Workshop, Khumaltar, Lalitpur, Nepal, August 11–13, 1998, pp. 35–58.

Yadav, R.L., Dwivedi, B.S., Pandey, P.S., 2000a. Rice–wheat cropping system: assessment of sustainability under green manuring and chemical fertilizer inputs. Field Crops Res. 65, 15–30.

Yadav, R.L., Dwivedi, B.S., Prasad, K., Tomar, O.K., Shurpali, N.J., Panday, P.S., 2000b. Yield trends, and changes in soil organic-C and available NPK in a long-term rice–wheat system under integrated use of manures and fertilizers. Field Crops Res. 68, 219–246.

Yoshida, S., Parao, F.T., 1976. Climatic influence on yield and yield components of lowland rice in the tropics. In: Climate and Rice. International Rice Research Institute, Philippines, pp. 471–494.
Zheng, J., 2000. Rice–wheat cropping system in China. In: Hobbs, P.R., Gupta, R.K. (Eds.), Soil and Crop Management Practices for Enhanced Productivity of the Rice–Wheat Cropping System in the Sichuan Province of China. Rice–Wheat Consortium Paper Series 9, Rice–Wheat Consortium for the Indo-Gangetic Plains. New Delhi, India, pp. 1–10.
Zhuang, H.Y., 1999. Effect of long-term minimal and zero tillages on rice and wheat yields, soil organic matter, and bulk density. Sci. Agric. Sin. 32, 39–44.