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Rice–Wheat Cropping Systems

Rajendra Prasad

Division of Agronomy, Indian Agricultural Research Institute,
New Delhi, India

I. INTRODUCTION

A. Global Population and Food Demand

Global population was 1 billion in 1800 A.D. and it took a whole century and 30 years to double itself by 1930 A.D. However, it took only 30 years to add another billion to reach 3 billion in 1960 A.D. and again in the next

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Table I
Demand for Meat and Eggs, Milk, Fish, and Feed in India at 5% GDP[a]

Item	1995	2000	2010	2020
		Million tons[b]		
Meat and eggs	3.1	3.7	5.4	7.8
Milk	64.0	75.3	103.7	142.7
Fish	4.7	5.7	8.2	11.8
Feed	14.2	16.8	23.7	38.1

[a]From Kumar (1998).
[b]All data in this paper are in metric ton, which is 1000 kg.

39 years it doubled itself to 6 billion in 1999. It is predicted that it will continue to increase and will double itself by 2100 A.D. to reach 12 billion (TOI, 2001). Most of this increase in population has been and will be in lesser developed countries in Asia, Africa, and South America, with Asia contributing the most. Some short-term projections are available from the World Bank and, according to their 1994–1995 population projections, the world population will increase from 5.7 billion in 1995 to 7 billion in 2020; the increase in China is likely to be from 1.2 to 1.5 billion, in south Asia from 1.3 to 1.9 billion, and in Africa from 0.7 to 1.3 billion (IFA, 1978). Obviously, this large increase in the world population will result in increased demand for food. According to the International Food Policy Research Institute (Pinstrup-Anderson *et al*., 1997), between 1993 and 2020 A.D. the global demand for cereals is expected to increase by 41%. It has been projected (IRRI, 1998) that annual rice production must increase from 556 million tons in 2000 A.D. to 758 million tons by 2020 A.D., a 36% increase (1.8% $year^{-1}$). Major rice-growing and rice-eating nations in south and southeast Asia must achieve a higher production growth rate. In addition to direct human consumption, the developing countries' demand for cereals for feeding livestock is expected to double during 1993–2000 A.D. due to increased demand for meat and other animal products, such as milk, butter, and cheese. Some of the factors contributing to the increased demand for animal products are economic growth, rising income, and urbanization. For example, China's per capita annual consumption of grains, meat, and edible vegetable oil was only 97.4, 4, and 1.7 kg, respectively, in 1949 and increased to 377, 42.8, and 21.2 kg, respectively, in 1998 (Jiaguo, 2000). Table I shows that the demand for meat, eggs, milk. and fish in India will almost double by 2020 A.D. from the present (2000).

The situation is further complicated by the fact that the increase in the production of cereals and other foods has to be made from the same or even lesser land due to an increased demand for land for housing, industry,

Table II
Available Arable Land (ha capita^{-1}) in RWCS[a] Countries

Country	1961	1990	2000	2020
Bangladesh	0.168	0.079	0.059	0.035
China	0.159	0.087	0.077	0.060
India	0.456	0.199	0.161	0.105
Nepal	0.191	0.121	0.095	0.059
Pakistan	0.330	0.169	0.126	0.069

[a]From Gill (1994).

railways, roadways, and so on; the pressure of this will be more in populous and predominantly rice–wheat cropping system (RCWS) countries such as China, India, Pakistan, and Bangladesh. Trends in per capita available arable land are shown in Table II. During the period 1961–2000 the per capita arable land in China declined from 0.159 to 0.077 ha and is predicted to decline further to 0.060 ha by 2020; thus it will be only 37.7% of that in 1961. Similarly, in India and Pakistan available arable land per capita by 2020 will be 23 and 21% of that in 1961, respectively. Other RWCS countries are not better off.

B. Rice–Wheat Cropping Systems

RWCS is a long-established grain production system in China; it was reported during the Tang dynasty (617–907 A.D.) and was widely adopted during the Song dynasty (960–1279 A.D.) and spread throughout the Yangtze River Valley in the Ming and Quig dynasties (1368–1911 A.D.) (Lianzheng and Yixian, 1994). However, the wheat yield following rice was only 0.7 to 1.0 tons ha^{-1} until the 1940s and it increased progressively after the 1950s as a result of improved varieties, better agronomic management, and pest control. Thus, in the Jiangou province, the average yield of wheat after rice was 1.6 tons ha^{-1} in 1970, 3.3 tons ha^{-1},in 1980, and 4.0 tons ha^{-1} in 1988 (Lianzheng and Yixian, 1994). The average wheat yield after rice in the Sichuan province in 1997 was 3.76 tons ha^{-1}, with the highest recorded as 6 tons ha^{-1} (Jiaguo, 2000).

RWCS in the Indian subcontinent is quite new and started only in the late 1960s with the introduction of dwarf wheat from CIMMYT, Mexico, which required a lower temperature (mean below 23 °C) for good germination than that required for traditional tall Indian wheat. Thus, wheat sowings were shifted from mid-October to mid-November, providing a full extra month for the preceding rainy season crop. This provided enough time for rice to mature; high-yielding varieties (HYV) of which such as IR-8 were already available. This set in the RWCS in the Indo-Gangetic plains (IGP) of the Indian subcontinent and the northwestern states of India [Punjab, Haryana, western Uttar Pradesh (UP)] and the Punjab and Sind province of Pakistan, which were traditionally wheat regions, were transformed into rice–wheat regions. The reverse of this happened in Bihar and West Bengal states of India and parts of Bangladesh, which changed from traditional rice regions to rice–wheat regions.

In RWCS two to three crops are grown during a span of 12 months or a crop year (July–June), as it is termed in India. In RWCS belt Indian subcontinent rice is grown during rainy season (July to November) when 700–1000 mm rainfall is received, while wheat is grown during the winter season (November to May) on stored soil moisture with supportive irrigation. In China, almost the same months are occupied by rice and wheat, although the rainfall pattern differs and, in some parts, quite a bit of rain is received during the wheat-growing season. Many farmers in India take a third crop of potato or toria in between rice and wheat or rice/mungbean/cowpea/green manure (GM)/sunflower in between wheat and rice. Some of the rice–wheat cropping systems are listed.

1. Rice (*Oryza sativa* L.)–wheat (*Triticum aestivum*)
2. Rice–potato (*Solanum tuberosum*)–wheat
3. Rice–toria (*Brassica campestris*)–wheat
4. Rice–wheat–mungbean (*Vigna radiata*)
5. Rice–wheat–cowpea (*Vigna unguiculata*)
6. Rice–wheat–green manure (*Sesbania* spp., *Crotolaria* spp.)
7. Rice–potato–wheat–green manure
8. Rice–wheat–sunflower (*Helianthus annuus*)
9. Rice–wheat–rice
10. Rice–vegetable peas (*Pisum sativum*)–wheat
11. Rice–vegetable peas–wheat–green manure
12. Rice–wheat–maize (*Zea mays*)

There could be many more variants involving vegetables and other short-duration crops. Most rice in RWCS is transplanted and rice varieties grown are of 90–140 days duration (seed to seed) of which 25–45 days may be spent in nursery; more aged seedlings (50 to 60 days old) are transplanted in some parts of China (Gupta *et al.*, 2000). Wheat in the cropping system takes 120 to 160 days; its maturity is determined by temperatures above 35°C, bright sunshine, and high wind velocity. Thus sown in mid-November (optimum for India), wheat matures by the end of March in eastern India, by the end of April in western Uttar Pradesh and Haryana, and by the first fortnight of May in Punjab and Himachal Pradesh. In China, wheat matures in June/July

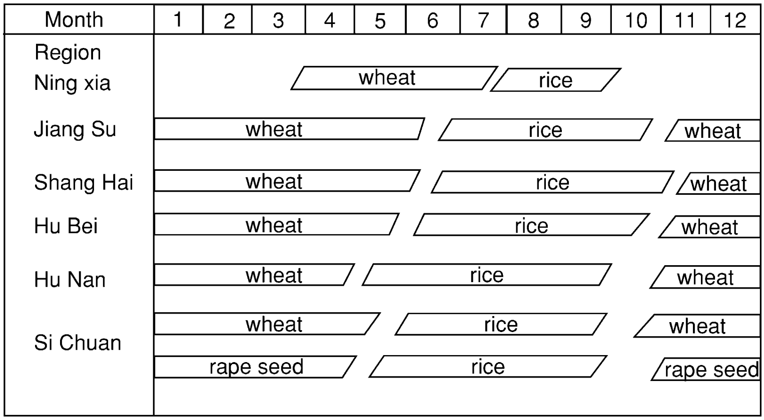

Figure 1 Crop calendar for RWCS in China. From Jiaguo (2000).

and thus receives quite a bit of rainfall asking for adequate drainage. It also delays rice transplanting, which is why the tradition of using older rice seedlings is used in some parts of China. A calender of RWCS in China for different regions is given in Fig. 1.

The estimates of area under RWCS in the world vary considerably. Paroda *et al*. (1994) reported 22.4 million ha (m.ha), whereas Ladha *et al.* (2000) reported 24 m.ha under RWCS. However, adding up the estimates available for different countries, it totals 28.8 m.ha: 13 m.ha in China (Jiaguo, 2000), 12.3 m.ha in India (Kumar *et al*., 1998), 2.2 m.ha in Pakistan, 0.5 m.ha in Nepal (Paroda *et al.* 1994), and 0.8 m.ha in Bangladesh (Ladha *et al*., 2000). These 5 RWCS countries are not just any 5 of the more than 200 countries of the world, they represent 43% of the world's population on 20% of the world's arable land (Singh and Paroda, 1994). Also, more than half of the world's malnourished people are in these countries. In the Indian subcontinent, RWCS is predominant in the Indo-Gangetic Plains (Fig. 2) (Woodhead *et al*., 1994), although there are pockets of this cropping system in several other states of India. The IGP are spread from 67° to 96°E longitude and from 20° to 33°E latitude (Schwartzberg, 1978). It extends from Assam and the Bay of Bengal on the east to the Afghan border and Arabian sea in the west and covers India, Bangladesh, and Pakistan. It has Himalayas in the north and minor hills or plateau in the south and covers about 2400 km from east to west and about 160 km wide in the east and 500 km in the west. In China, RWCS is predominantly in the Yangtze River Valley (Fig. 3). In India, as well as in China, areas under RWCS have spread over time. Data on the spread of the area under RWCS in India in 1983 and a decade later in 1993 under RWCS are given in Table III. In the states of

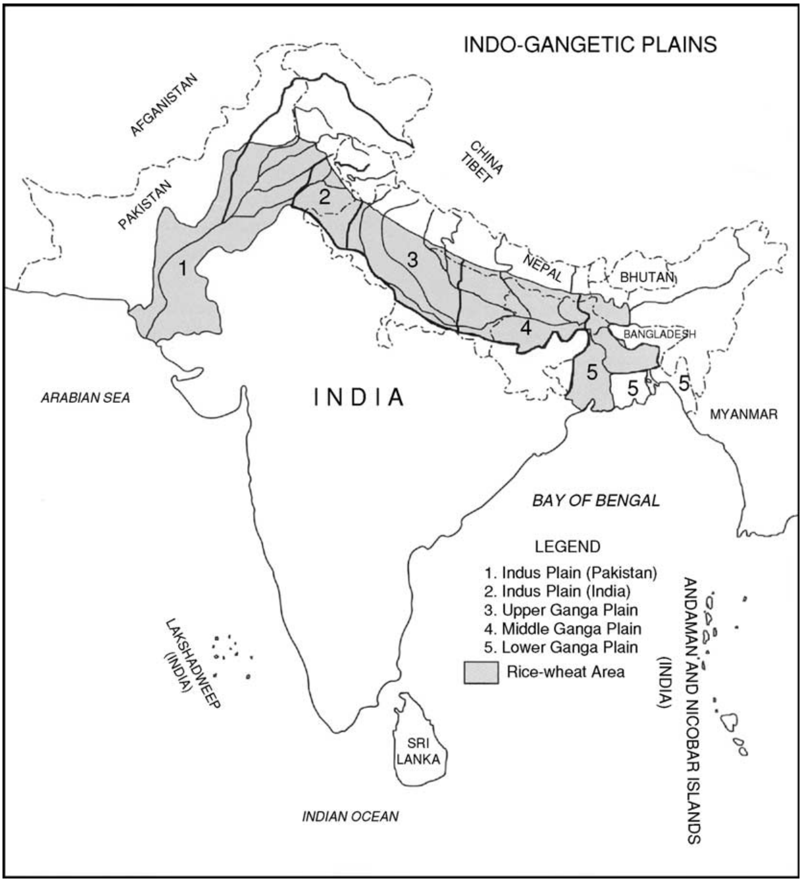

Figure 2 RWCS belt of the Indo-Gangetic Plains of the Indian subcontinent. From RWCS Int. Workshop, New Delhi, India, September 25–27, 2000. Ministry of Agriculture, Gurtiy India, Indian Council of Agricultural Research, and the World Bank.

Punjab, Haryana, and UP, which are predominantly wheat-growing states, almost all rice is under RWCS. However, in West Bengal, which is a predominantly rice-growing state, only 4% of the area under rice is under RWCS. The reverse is true when the area under RWCS is expressed as the percentage of total wheat area in these states. In Bihar and West Bengal, the wheat area under RWCS is 96–98% of the total wheat area; in Punjab and UP, the values are 63 and 61%, respectively, whereas in Haryana it is only 36%. This is because wheat also follows rainy season fallows, sorghum (*Sorghum bicolor*), maize (*Zea mays*), pearl millet (*Pennisetum typhoides*), cowpea, mungbean, pigeonpea (*Cajanus cajan*), and so on, in UP, Punjab,

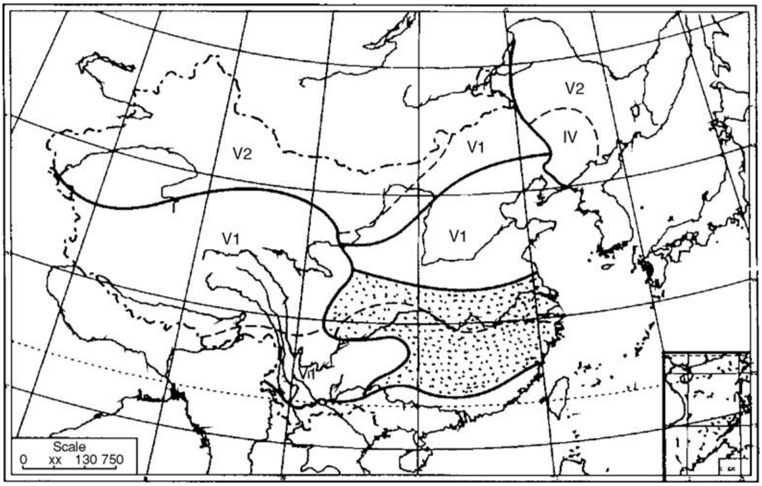

Figure 3 RWCS belt (filled area) of China (mainly in the Yangtze river valley). From Jiaguo (2000).

Table III
Estimated Area under Rice–Wheat Cropping System in the Indo-Gangetic Plains in India[a,b]

	Area (m ha) of rice–wheat system		Rice–wheat rotations area as percentage of total rice area		Rice–wheat rotations area as percentage of total rice area	
States	1983	1993	1983	1993	1983	1993
Punjab	1.35	2.02	100	100	44	63
Haryana	0.51	0.67	100	100	30	36
Uttar Pradesh	5.14	5.25	94	96	61	61
Bihar	1.70	1.90	37	40	96	96
West Bengal	0.11	0.26	2	4	41	98
Indo-Gangetic plain	8.82	9.96	72	75	58	63
India	11.46	12.33	29	30	49	52

[a]Average of triennium ending 1983 and 1993.
[b]From Kumar *et al.* (1998).

and Haryana. Yadav *et al.* (1998a) showed that RWCS in India is prevalent in about 120 out of a total of 502 districts, whereas rice–rice is practiced in only about 50 districts. Other cropping systems, such as maize–wheat, sorghum–wheat, rice–rape (*Brassica* spp.), and sugarcane–wheat, are practiced in still fewer districts.

In China, RWCS accounts for 41.5% of the total area of 31.3 m.ha under rice (Jiaguo, 2000). Taking all the five countries (China, India, Pakistan, Bangladesh, and Nepal) together, RWCS covers 28% of the total rice area and 35% of the total wheat area in these countries.

C. Contribution to Food Security

RWCS covers about 32% of the total rice area and 42% of the total wheat area in four countries of south Asia (India, Pakistan, Bangladesh, and Nepal) and accounts for one-quarter to one-third of the total rice and wheat production (Ladha *et al.*, 2000).

More detailed information on this is available from India where it is the backbone of the country's food security. In 1983, the total production from RWCS was 35.6 million metric tons, which was 28.3% of the total cereal production in India (Table IV); the production increased to 50.4 million metric tons in 1993, accounting for 31.4% of the total cereal production in that year. In India, rice and wheat are procured by the government for distribution through the public distribution system (PDS). In 1994–1995, RWCS in the IGP of India contributed 94.9% of the total wheat procurement and 59.6% of the total rice procurement by the government of India for distribution through the PDS (Kumar *et al.*, 1998). This share of RWCS to PDS in India is continuing even today. Thus, RWCS is the key for India's food self-sufficiency.

Table IV
Contribution of Rice–Wheat-Based Cropping System (RWCS) in Total Cereal Production in Indo-Gangetic Plains of India[a]

	Production from RWCS (mt)[b]		Total cereal production (mt)		Contribution of RWCS in total production (%)	
States	1983	1993	1983	1993	1983	1993
Punjab	8.2	14.1	13.9	19.7	59.0	74.6
Haryana	2.6	4.3	6.2	9.4	41.9	45.7
Uttar Pradesh	14.8	20.5	24.0	33.2	61.7	61.7
Bihar	3.9	5.5	7.7	8.9	58.6	61.8
West Bengal	0.9	1.1	6.9	12.4	13.0	8.9
Indo-Gangetic plain	29.9	44.7	58.7	83.6	50.9	53.5
India	35.6	50.4	125.6	160.7	28.3	31.4

[a]From Kumar *et al.* (1998).
[b]Million metric tons.

In China, the contribution of RWCS toward total cereal production from rice-based cropping systems was about 50%, which was roughly about one-fourth of the total cereal production in the country (Lianzheng and Yixian, 1994).

II. CLIMATE AND SOILS

RWCS is generally practiced in subtropical to subtemperate regions with warm humid summers and dry cold winters. There is a west-to-east zoning in the IGP of the Indian subcontinent. Rainfall ranging from 700 to 1000 mm year^{-1} is mostly received during June to September, with rainfall increasing eastward. Some rains (5–10% of the annual total) are received during winters (November–March) in some areas. As already mentioned, rice in the Indian subcontinent is grown during the rainy season (June–September) and fall (September–October), whereas wheat is grown during the winter (November to February) and spring (March–May). Growing seasons of wheat are longer in the west (195 days, mid-November to the end of May) and shorter in the east (135 days, mid-November to the end of March). Wheat in the RWCS belt in the Indian subcontinent is grown under irrigation.

In China there is a north-to-south zoning in RWCS regions. The growing season of wheat is longer in the north (220 days, early October to mid-June) and shorter in the south (160 days, early November to mid-May). In northern China, as in Beijing, wheat season rainfall may be only 150 mm (35 mm month^{-1} during February–April), which is not sufficient for wheat, and irrigation is a must. However, in the middle and lower reaches of the Yangtze River, wheat season rainfall is 500–700 mm, which, in the absence of adequate drainage, results in fatal water logging of wheat. A good drainage system is a prerequisite for wheat in this zone (Lianzheng and Yixian, 1994).

Both in the IGP and in the Yangtze river valley in China, the soils are formed from the river alluvium. In the IGP, soils could be Alfisols (Haplustalfs, Ochroqualfs), Inceptisols (Ustochrepts), Entisols (Aquents, Fluvents, Psamments), and Mollisols (Hapludoll) with soil textures ranging from loamy sands to clay loams. In India, RCWS is also practiced in pockets outside IGP in the states of Madhya Pradesh (Chromosterts), Rajasthan, Maharashtra, and Gujarat (Torrifluvents, Haplargid, Ustochrepts, Dustochrepts, Chromostarts). Large areas under RWCS in IGP and elsewhere are saline-sodic, which is one reason why rice is quite popular as a rainy season crop.

In China, soils of RWCS regions are more weathered and are referred to as red soils, yellow earths, purple soil, and limestone soil (Zitong, 1986).

Red and yellow soils could be Alfisols or Entisols, whereas dark/purple colored soils are vertisols such as Shajiang black soils in Jingsu and other provinces. The clay content in black soils could vary from 40 to 70%, making soil management very difficult, particularly for wheat after rice.

III. AGRONOMIC MANAGEMENT

A. Tillage and Transplanting/Seeding

1. Rice

In the RWCS belt of the Indian subcontinent, most rice is transplanted. Unless a third crop is taken between wheat and rice, there is plenty of time (about 2 months) for preparing fields for rice, which is generally done 1 to 2 weeks before transplanting (first week of July). Where mechanization is practiced, the dry field is disked twice with an offside disk and is then harvested or cultivated twice and leveled. Where animal power is used, the land is prepared after giving one light irrigation. Generally two to three harrowings are done with a country plough and the land is leveled. The field is then ponded with water and is puddled with a puddler and leveled again. Two to three 21- to 25-day-old rice seedlings per hill are then transplanted at a spacing of 20 × 10 cm or 15 × 15 cm. Rice seedlings are raised separately on a site near the tube well so that the nursery can be irrigated frequently. For each hectare of land, a nursery area of 1000 m^2 and 25–30 kg seed is required. Nurseries are well manured with farmyard manure and chemical fertilizers. Also, one or two hand weedings are given.

There have been some studies in India on direct seeding on a dry seed bed (Chatterjee and Mukherjee, 1970; Sudhakara and Prasad, 1986) or sowing sprouted seeds on a puddle seedbed (Narhari and Pawar, 1961; Nayak and Garnayak, 1999). These techniques, although time and energy saving, have not yet found favor in the RWCS belt due to serious weed problems. Farmers, particularly those in a less favorable environment (LFB), who are not economically well off do not have enough funds to spend on herbicides.

The land preparation is similar in China but many farmers broadcast rather than transplant rice. For this purpose, seedlings are raised in special 60 × 30-cm PVC trays that contain shallow depression or cones with a 2-cm-diameter top and a 1-cm-diameter bottom. These cones are 1–1.5 cm deep with a hole at the bottom for drainage. Two to three seeds are placed and grown in each cone. The 20- to 25-day-old seedlings are broadcast manually or with the help of a blower in a puddled rice field. Some gap filling is done manually (Gupta *et al*., 2000). This technique reduces the labor requirement for transplanting considerably. In regions when rice transplanting is delayed due to delayed wheat harvest, about 60-day-old seedlings are used for transplanting (Jiaguo, 2000). Some farmers practice twice culture for raising a rice nursery. First, young seedlings are raised for 7–10 days in a greenhouse using 500 seeds m^{-2}. These young seedlings are then transferred to a nursery at a spacing of 5×5 cm and are raised there for 40–45 days before transplanting in the rice field. In this case, because rice grows in the field for fewer days (60–70 days), the irrigation requirement is reduced considerably.

2. Wheat

In RWCS there is very little turn-around time between rice harvest and wheat sowing. Depending on the variety and date of transplanting, rice is harvested between the end of October and the end of November, whereas the optimum time of sowing wheat in India is mid-November and in China it is the last week of October to the first week of November. Depending on the time of harvest of the rice crop, conventional tillage requires presowing irrigation on well-drained soils or draining or drying of soil in lowlands followed by one or two diskings, two harrowings, and leveling. All these operations require time and delay sowing of wheat, which results in a reduced yield (Figs. 4 and 5). Zero-till techniques are therefore being tested and adopted where suitable and advantageous.

In the Sichuan province of China, surface seeding of wheat and rice straw mulching is practiced (Yonglu *et al*., 2000). This practice saves 22% in costs and 23% in labor and increases rice yield by 10% and farmers income by 35%. Some farmers in India also do surface broadcasting of wheat immediately after rice harvest and without preparatory tillage, but most wheat in the Indian subcontinent is sown after conventional tillage. Available data from Pantnagar (Rath *et al*., 2000), New Delhi (Singh *et al*., 2001), Ludhiana (Samra and Dhillon, 2000), and Modipuram (Prasad and Yadav, 2000) also show its advantage (Table V). Kumar (2000) from Pantnagar recommended a minimum of two passes of a harrow followed by two passes of a cultivator and one leveling for seed bed preparation for wheat after rice. In a study at Pantnagar (Singh and Gangwar, 2000), although the grain yield and benefit cost ratio was higher under conventional tillage, zero tillage was recommended due to savings in cost, time, labor, fuel, and energy consumption (Table VI).

However, in 132 trials conducted on the farmers' fields in Haryana, Mehla *et al*. (2000) found a 7.1% increase in the grain yield of wheat with zero tillage (ZT) over conventional tillage (CT) sowings on the same date (Table VII) and 16.7% when conventional tillage was done and sowings were delayed by about 2 weeks (CTD), as is the traditional farming practice,

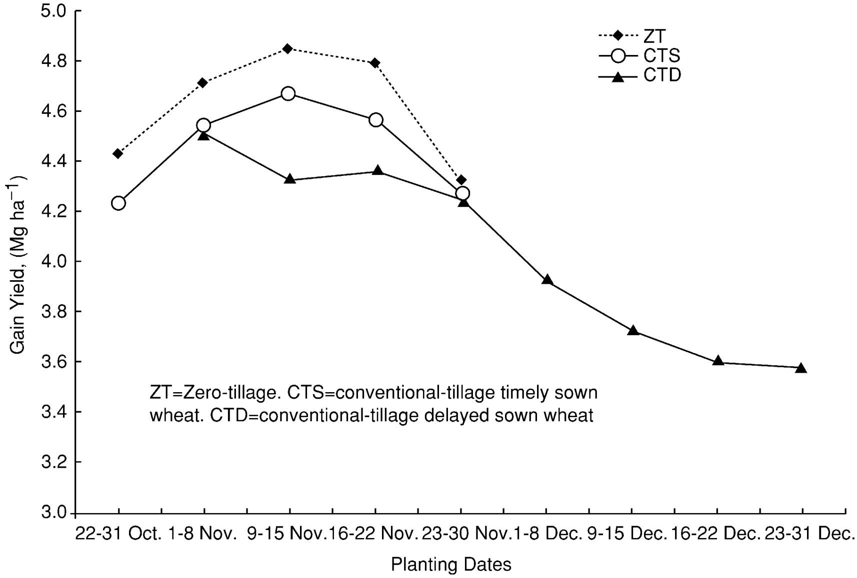

Figure 4 Effect of planting dates and tillage options on the productivity of wheat Cultivar PBW 343, From Mehla *et al.* (2000).

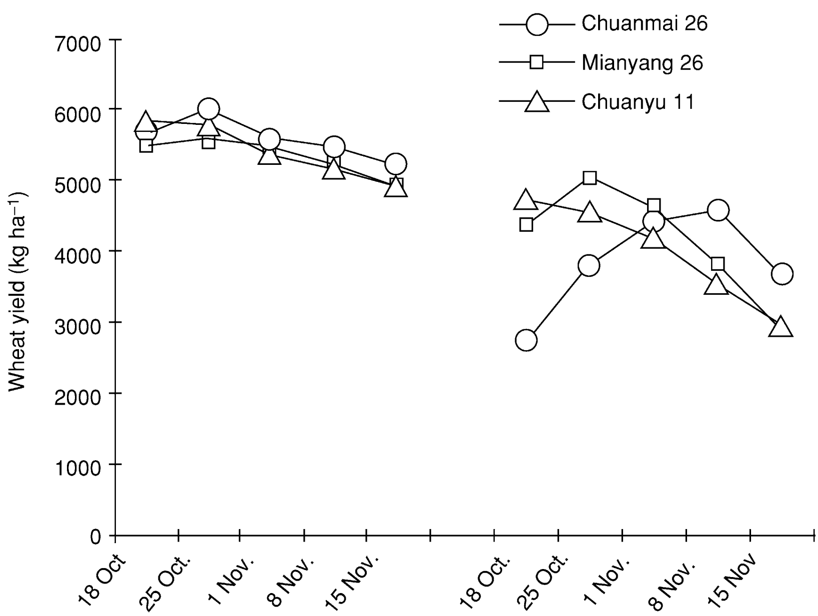

Figure 5 Effect of sowing date on the yield of wheat in China in 1997 (left) and 1998 (right). From Yonglu *et al.* (2000).

Table V
Grain Yield (t ha^{-1}) of Wheat as Affected by Tillage

	New Delhi[a]			Pantnagar[b]		Modipuram[c]		Ludhiana[d]
Tillage	1994	1995	1996	1998	1999	1997	1998	1996 and 1997 mean
Zero tillage	4.2	3.6	3.2	3.6	3.8	3.4	1.6	4.8
Conventional tillage	4.6	4.1	3.3	4.6	5.2	4.4	2.3	5.0
LSD (0.05)	0.17	0.09	NS	0.07	0.10	NA	NA	NS

[a]From Singh and Prasad (2000).
[b]From Rath *et al.* (2000).
[c]From Prasad and Yadav (2000).
[d]From Samra and Dhillon (2000).

Table VI
Comparative Performance of Conventional and Zero Tillage in Wheat After Rice[a]

Factors	Conventional	Zero till	Savings over conventional (%)
Time (h/ha)	5	2	60.0
Labour (h/ha)	12	6	55.3
Diesel (l/ha)	30.2	10	50.0
Energy (K cal/ha)	480,567	146,042	66.9
Cost of sowing (Rs/ha)	895	400	69.6
Grain yield (t/ha)	4.2	3.0	
Benefit:cost ratio	2.5	2.3	

[a]From Singh and Gangwar (2000).

where sowings are delayed because a presowing irrigation is given and it takes time for the soil to come to condition for preparatory tillage. Similarly, in 338 frontline demonstrations on the farmers fields during 1998–2001 carried out throughout India under the All India Coordinated Wheat Improvement Project (AICWIP), zero tillage gave 8.1 to 35.5% higher yields (Table VIII). The increase in returns over variable cost was 1882 Indian Rupees ha^{-1} (Table IX). Similarly, in a village adopted by the Banaras Hindu University in eastern UP (Village Karhat, District Mirzapur), the farmers harvested an average of 4.8 tons ha^{-1} of wheat using zero-till technology; it was claimed to be the best crop in the entire district (Joshi *et al.*, 2001).

In the Haryana state of India, zero-till technology spread from a few hectares in 1997–1998 to more than 8000 ha in 1999–2000 (Mehla *et al.*,

Table VII
Relative Performance of Zero Tillage (ZT) and Conventional Tillage (CT) on the Grain Yield of Wheat on Farmers' Field in this Haryana State of India[a]

			Grain (t ha^{-1})			*Phalaris minor* plant m^{-2}	
District	Year	Trials (number)	ZT	CT	CTD	ZT	CT/CTD
Kaithal	1997–1998	04	4.4	3.8	3.6	129	560
	1998–1999	32	4.9	4.6	4.3	114	550
Karnal	1997–1998	17	4.4	3.8	3.5	103	438
	1998–1999	32	4.6	4.5	4.3	110	473
Sonepat	1998–1999	07	3.5	3.3	2.0	75	333
Panipat	1998–1999	06	3.8	4.0	3.6	89	440
Ambala	1998–1999	02	3.8	3.6	3.0	73	379
Kurukshetra	1998–1999	32	4.6	4.4	4.0	97	442
Mean			4.2	3.9	3.5		

[a]From Mehla *et al*. (2000).

Table VIII
Performance of Zero Tillage over Conventional Tillage in Seeding Wheat in 338 Frontline Demonstrations on Fields in India (Average over 3 Years of Data from 1998–1999 to 2000–2001)[a]

	Wheat grain (t ha^{-1})		
Zone	Zero tillage	Conventional tillage	Yield gain (%)
Northwest plains (states of Punjab, Haryana, western UP, Delhi, and Rajasthan)	4.95	4.58	8.1
Northeast plains zone (states of Bihar, West Bengal, Orissa, Assam, and eastern UP)	3.69	2.72	35.5
Central zone (states of MP, Gujarat, and parts of Rajasthan)	5.05	4.52	11.8

[a]From Singh and Kharub (2000).

2000). Similarly, in the Sichuan province of China, the area under zero till increased by about 146,000 ha annually during the 1990s (Yonglu *et al*., 2000). This has been possible due to the development of zero-till machines in both China and India. Thus, over time, zero-tillage is likely to spread in the RWCS belt in most countries.

Another new wheat-seeding technology in RWCS in India is the furrow irrigated raised bed (FIRB). This was introduced from Sonora, Mexico,

Table IX
Comparative Economics (Indian Rupees (Rs) ha^{-1}) of Zero Tillage (ZT) and Conventional Tillage (CT) in Frontline Demonstrations on the Farmers' Fields in Northwest Plains Zone[a]

Working cost		Gross output		Returns over variable cost		
ZT	CT	ZT	CT	ZT	CT	Difference
9338 (485.3)[b]	9612 (392.6)	36550 (592.9)	34958 (671.4)	26652 (524.5)	24770 (529.4)	1882[c]

[a]From Singh and Kharub (2001).
[b]Standard error.
[c]Significant at 1%.

Table X
Effect of Tillage Practices on Soil Physical Properties, Soil Moisture Conservation, and Soil Fertility at Changdu (China)[a]

		Porosity at tillering		Soil moisture (%)		Soil fertility	
Tillage	Soil layer depth (cm)	Total (%)	Capillary (%)	Tillering	Jointing	Organic matter (%)	Total N (%)
Zero till	0–7	49.4	46.7	20.1	24.3	1.62	0.154
	7–15	50.1	44.4	19.5	24.4	1.68	0.131
Conventional	0–7	54.7	41.2	19.9	20.8	1.67	0.108
	7–15	54.3	41.6	20.5	24.7	1.55	0.105

[a]From Yonglu (2000).

where about 1 million acres of wheat are grown under FIRB. A specially designed raised bed planter is required for this purpose and is now locally made in India. The planter makes 70-cm-wide beds (for two to three rows of wheat) with an irrigation furrow in between. The FIRB system gives a 5–10% higher yield over conventional sowing and brings considerable savings in irrigation water and also facilitates manual weeding (Kumar *et al*., 2001).

The advantages of zero-till technology are many. Some of these are as follows.

1. Less time required for sowing
2. Less labor requirement
3. Lower costs
4. Less diesel requirement
5. Less energy requirement
6. Avoidance of delay in wheat sowing
7. Improved soil physical and chemical properties (Table X)

8. Soil moisture conservation
9. Reduction in the population of *Phalaris minor* (Table VII)
10. Higher yield and income.

However, adequate weed control measures with the help of herbicides and fertilizer nitrogen are required for a successful wheat crop with zero-till after rice.

B. Crop Residue Management

Due to a short turn-around period between two crops in RWCS, crop residue management is a serious problem. In the Indian subcontinent the major problem is the management of rice residue, as rice is harvested during the end of October to the end of November, whereas the optimum sowing period of wheat is mid-November. As a contrast, there is a gap of 2 months between wheat harvest and rice planting and the wheat residue can be removed easily, However, wheat residue management becomes a problem if a third crop (rice/mungbean/cowpea/greengram) is taken during summer. The problem of crop residue management has become more serious due to combine harvesting of the crops, which leaves 15- to 25-cm-tall stubbles and spreads the rest of the straw on the field. Most farmers therefore burn the rice/wheat residue in the field.

In China, crop residue management is a problem for both rice and wheat. Rice is harvested in October/November and wheat is sown in November/December, leaving a small turn-around period as in the Indian subcontinent. Again, wheat is harvested in June/July, while rice is transplanted in July, which leaves very little time for land preparation. Burning of crop residue is therefore the most common practice.

Due to increasing concerns about depleting soil fertility in RWCS, which is being held responsible for a declining rice/wheat yield (Duxbury *et al.*, 2000; Nambiar, 1995; Yadav, 1998), and with the availability of zero-till seed drill for seeding wheat after rice, a number of studies have been made in India in the 1990s on the effect of residue incorporation vis-à-vis its burning or removal on rice/wheat yields and on soil fertility.

At New Delhi (Prasad *et al.*, 1999a), Karnal (DWR, 2000–2001), and Kaul (Dhiman *et al.*, 2000), incorporation of rice and/or wheat residues showed beneficial effects on the yield of rice. Data from Kaul are given in Table XI. In the case of wheat in the initial year there was poor growth in residue incorporated plots, but no such effects were seen in later years. There was an increase in grain yield of 0.6 tons ha^{-1} in the rice–wheat cropping system. These results show that crop residues can be incorporated without any detrimental effects on crops in RWCS. The little disadvantage seen in wheat due to cool winter temperatures, slowing decomposition of rice

Table XI
Effect of Rice (R) and Wheat (W) Residue Management on Grain Yield (t ha^{-1}) of Rice and Wheat in RWCS at Kaul[a]

	1994–1995		1995–1996		1996–1997		Mean		
Treatment	R	W	R	W	R	W	R	W	Total
Residue[b] removed	7.0	3.8	6.2	3.9	7.3	4.3	6.8	4.0	10.8
Residue burnt	7.0	4.3	6.1	3.4	7.2	4.5	6.8	4.1	10.9
Residue incorporated	7.7	3.6	6.7	3.7	7.7	4.9	7.4	4.1	11.5
LSD (P=0.05)	0.30	NS	0.26	0.29	0.31	0.28			

[a]From Dhiman *et al.* (2000).
[b]Both rice and Wheat Residues in Respective Years.

Table XII
Effect of Crop Residue Management on Soil Fertility after Five Cycles of RWCS at Pantnagar[a]

		Total nutrients (g kg^{-1})			Available nutrients (mg kg^{-1})		
Treatment	Organic C (g kg^{-1})	N	P	K	N	P	K
Residue incorporation	7.8	0.73	0.59	16.0	118	11.4	85.4
Residue burning	5.4	0.68	0.58	15.3	119	11.1	81.8
Residue removal	5.3	0.65	0.51	14.5	110	9.3	72.3
LSD (P=0.05)	0.2	0.03	0.05	0.2	3.6	1.1	2.7

[a]From Sharma *et al.* (2000).

residue and immobilization of soil and fertilizer nitrogen, can be overcome by applying some additional fertilizer N by 40 kg ha^{-1} (Brar *et al.*, 2000) or by intercropping legume-enriched cereal residues (Sharma and Prasad, 2001). Chauhan *et al.* (2001) also recommended 25% higher nitrogen for zero-till seeding of wheat.

The major advantage of incorporation of rice/wheat residue is the increase in soil organic C (Dhiman *et al.*, 2000; Prasad *et al.*, 1999). In a study at Pantnagar (Sharma *et al.*, 2000) after five cycles of RWCS, organic C, total N, total K, and available K were significantly higher in plots receiving crop residues as compared to plots where residue was burned or removed (Table XII). Sharma *et al.* (2000) from Delhi reported that an incorporation of crop residue also reduced the bulk density of soil. These results are similar to those reported from the United States, European countries, and Australia on residue incorporation in other cropping systems (Prasad and Power, 1991).

C. Nutrient Management

Nutrient management is crucial for high yields in RWCS. Work at New Delhi showed that for each metric ton of grain produced in RWCS, 20–22 kg N, 2–3 kg P, and 25–29 kg K are removed from the soil (Aipe and Prasad, 2001; Gangiah and Prasad, 1999); the total grain production (rice + wheat) in these studies varied from 5 to 8 tons ha^{-1} and total NPK removal from 257 to 406 kg ha^{-1}. At Pantnagar where a grain yield of 9.8 tons ha^{-1} (rice + wheat) was recorded, NPK removal was 522 kg ha^{-1} (Nambiar, 1994). In addition to NPK, large amounts of micronutrients are also removed, although the information available on this is limited. At Pantnagar, RWCS removed 7162 g Fe, 1325 g Mn, 1145 g Zn, and 636 g Cu ha^{-1} (Nambiar, 1994). Many farmers in the RWCS belt in the Indian subcontinent harvest 7–8 tons ha^{-1} of rice and 5.6 tons ha^{-1} of wheat, leading to a heavy removal of plant nutrients. The general recommendation in the RWCS belt in the Indian subcontinent is 120 kg N and 13 kg P ha^{-1} for rice and 120 kg N and 26 kg P ha^{-1} for wheat. Potassium is generally not included in the recommendation and when it is the rates are only 25–50 kg K ha^{-1}. Thus total NPK addition to RWCS adds to only 279 to 329 kg ha^{-1}, which is far less than removal. At Pantnagar, an annual negative balance of 22 kg N, 10 kg P, and 242 kg K ha^{-1} was recorded (Nambiar, 1994). Thus, over years, nutrient depletion of RWCS soils can be a serious problem and can affect crop productivity. This would also explain why Zn and Mn deficiencies were first reported from the RWCS belt in India.

In the Sichuan province of China, where mostly hybrid rice is grown, the average yield was 7.85 tons ha^{-1}, with the highest recorded being 10 tons ha^{-1}. The average yield of wheat was 3.76 tons ha^{-1}, whereas the highest recorded was 6 tons ha^{-1}. Thus the highest grain production in RWCS was 16 tons $ha^{-1}year^{-1}$ (Jiaguo, 2000). Nutrient removal per ton of grain produced was 21 kg N, 10 kg P, and 19 kg K (Shihua and Wenquiang, 2000). In China, there is considerable emphasis on organic manures. Recommendations in RWCS in the Sichuan Province are 22.5 tons of fine liquid dung, 30 tons of synthetic manure (bean meal, seed cake, etc.), 180 kg N, 20–33 kg P, and 150–187 kg K per hectare for a grain yield of 6 tons ha^{-1} (Yonglu *et al.*, 2000). Farmers desiring higher yields must increase manure and fertilizer proportionately. The recommended ratio of organic manure to chemical fertilizer is 4:6 (on nutrient basis). These higher recommendations of fertilizer and the inclusion of organic manures could be the secret of sustainability of RWCS in China.

A large number of experiments have been conducted in India on the nutrient management in rice and wheat crops individually and to review them entirely is beyond the scope of this chapter. A few references are cited here to bring out the main points with reference to RWCS.

1. Nitrogen

Nitrogen is the key plant nutrient and good responses are obtained in both rice and wheat. The general recommendations are 100–120 kg N ha^{-1} for each crop in the RWCS. Many farmers in the RWCS belt apply 150 kg N ha^{-1} or even more to rice. One of the main factors responsible for this is the low recovery of N applied to rice (Cassman *et al.*, 1998; Prasad, 1999). Using ^{15}N, George and Prasad (1989) showed that the recovery of N applied to rice was 31.0, 26.7, and 25.9% at 50, 100, and 150 kg N ha^{-1}. Goswami *et al.* (1988), also using ^{15}N, showed that the recovery of 60 kg N ha^{-1} applied to rice was 35.4% by rice and 4.1% by the succeeding wheat crop (residual N); the corresponding value at 120 kg N ha^{-1} was 31.2% by rice and 4.6% by the succeeding wheat crop (residual N). The recovery of N applied to wheat is higher and varies from 40 to 91% (Prasad *et al.*, 1998).

a. Causes for Low N Recovery. The main causes for low recovery of N in RWCS are (1) ammonia volatilization, (2) denitrification, (3) leaching, and (4) runoff and erosion (Prasad and Power, 1995, 1997). Because processes other than ammonia volatilization are more operative in the rice-growing season, when monsoon rains are received or heavy and frequent irrigations are applied, losses of N are more in rice, leading to a lower recovery of N applied to rice than to wheat.

Once urea is applied to a moist soil it hydrolyzes rapidly under subtropical conditions where rice and wheat are grown; most hydrolysis is over by 2 to 4 days (Fillery *et al.*, 1986; Reddy and Prasad, 1975). At New Delhi, 8.5% of the applied urea-N was lost as ammonia during the first week after fertilizer application in the initial stages of rice growth (Sudhakara and Prasad, 1986a). Similarly, Sarkar *et al.* (1991) reported a loss of 15–20% of applied N when urea was broadcast in a wheat field. Simulating wheat- and rice-growing conditions in the laboratory, Prasad *et al.* (1999) reported a loss of 4.4% of applied N after 1 week of incubation when urea was broadcast, whereas it was 0.05% when urea was deep placed under well-drained conditions as obtained in wheat. Under submerged rice conditions, the loss of N due to ammonia volatilization after 1 week of incubation was 13.5% of applied N when it was broadcast on the surface. These losses can be reduced when urea is coated with neem or blended with a nitrification inhibitor (Prasad and Power, 1995; Sudhakara and Prasad, 1986b). The addition of pyrite, which is reported to have some nitrification-inhibiting properties (Blaise and Prasad, 1993), can also reduce ammonia volatilization. Neem (*Azadirachta indica* Juss) cake or oil coating of urea and use of pyrites are simple indigenous technologies for the Indian subcontinent and can be adopted easily in RWCS.

In China, ammonium bicarbonate is an important source of N, and ammonia volatilization losses from this fertilizer are likely to be high (Shihua and Wanquiang, 2000).

Once urea is hydrolyzed and the resultant ammonia-N is nitrified, denitrification follows under submerged anaerobic rice-growing conditions. Denitrification is one of the major mechanisms of N loss from the soil and these losses can range from negligible to as high as 100 kg N ha^{-1} (Aulakh *et al.*, 1992). Denitrification losses are the most under lowland rice conditions and range from little to as high as 64% of available N (Buresh and De Datta, 1990; De Datta and Buresh, 1989; Mohanty and Mosier, 1990). Losses from wheat fields in Canada and Europe varied from 1 to 33 kg N ha^{-1} (Aulakh *et al.*, 1992). The best way to reduce denitrification losses is to use synthetic or natural nitrification inhibitors such as Nitrapyrin, DCD, neem cake or oil, and pyrites (Prasad and Power, 1995).

There is not much information available on leaching losses of N. In a pot-culture study, the leaching loss was 11.5% of applied urea N and was reduced to 8.7% when urea was coated with neem cake (Prakasa Rao and Prasad, 1980). In a field study at Pantnagar on a silty clay loam soil, 12% of applied N was lost by leaching and these losses were reduced to 8% when urea was blended with neem cake (Singh and Singh, 1986). Leaching losses of N can be reduced by using slow-release fertilizers such as sulfur-coated urea, urea-form, isobutylidene diurea (Prasad *et al.*, 1971), or neem cake or oil-coated urea (Prasad *et al.*, 1993, 1999).

Data on losses of N due to runoff and erosion in RWCS are not available, but the occurrence of such losses is well known to the farmers, which is the reason why farmers in the upper regions of a landscape do not apply heavy doses of fertilizer N. Slow-release N fertilizers would be ideal for such situations, but unfortunately these are not yet available to rice farmers at an appropriate price.

b. Ways to Increase N Use Efficiency. Because N (or any other plant nutrient) use efficiency depends on the crop yield obtained, all agronomic management practices, such as date of sowing, plant population, water management, and weed management, need to be optimized and adequate plant protection needs to be provided to rice as well as to wheat in RWCS (Prasad, 1990).

Application of N in small amounts is a proven tool to increase N use efficiency. Most N to rice or wheat is applied in two or three split doses. In rice, where N losses are more, the number of splits can be increased. The general recommendation for rice in the RWCS belt is half dose at transplanting or a week after transplanting and the rest half dose at panicle initiation (Prasad *et al.*, 1970; Thakur and Kushwaha, 1970; ten Have, 1971). In the case of very long duration rice varieties, there could be three split doses: half at transplanting, one-fourth at active tillering, and the rest at panicle emergence/flowering. However, in China the recommendation is to apply 70% at transplanting and the rest 30% one week after transplanting (Shihua and Wenqiang, 2000).

The general recommendation for N application in wheat in India is in two split doses: half at sowing and half at first irrigation (21–25 days after sowing) (Bhardwaj, 1978). On very sandy soils, three split doses may be used. In China, 70% of the N dose is applied at sowing, 15% at the two-leaf stage, and the final 15% at jointing (Shihua and Wenqiang, 2000).

Deep placement of N (5–8 cm below the surface) or application as pellets has been found to be significantly superior to broadcasting of urea at the surface (Prasad *et al*., 1970). Incorporation in soil is another method used to reduce the loss of applied N (Schnier *et al*., 1988, 1990). The bulk of fertilizer N in rice is still broadcast in most rice-growing countries. As regarding wheat, most farmers in the RWCS belt in the Indian subcontinent use a fertilizer-cum-seed drill and place the basal dose 4–5 cm below and to the side of the seed. This reduces ammonia volatilization losses associated with the broadcast application of N.

As regarding sources of N, fertilizers containing nitrate-N are inferior to ammoniacal and amide-N-containing fertilizers for rice (Prasad *et al*., 1998). Sarkar *et al*. (1978) and Prakasa Rao and Prasad (1982) reported that ammonium sulfate was superior to urea. However, urea is the dominant source for nitrogen for rice in Asia due to a higher N content, less production and transportation costs, no need for other raw materials, such as sulfur, in the manufacture of ammonium sulfate, and compatibility with herbicides and pesticides for foliar application. For wheat, most N carriers are equally effective (Singh and Prasad, 1985).

The role of slow-release fertilizers and urea supergranules in increasing N use efficiency has already been discussed and there are many reports for rice (Buresh, 1987; Prasad *et al*., 1971b; Shoji and Kanno, 1994; Stutterheim *et al*., 1994; Wada *et al*., 1991). Considering their importance and the role that these materials can play globally in increasing fertilizer N use efficiency and in reducing associated environmental hazards, the International Fertilizer Association in Paris has published information on controlled release and stabilized fertilizers in agriculture (Trenkel, 1997). As regarding indigenous materials, there has been considerable research in India on neem cake-coated urea (NCU) and the matter has been reviewed (Prasad *et al*., 1993). In rice at 100 kg N ha^{-1} the increase in yield due to NCU over uncoated urea was 11.1% (Reddy and Prasad, 1977) to 54.2% (Surve and Daftardar, 1985). Similarly, in wheat at 80 kg N ha^{-1} NCU produced 5.4% more grain than uncoated urea (Agarwal *et al*., 1990). Furthermore, application of NCU to rice results in residual effects in wheat (Prasad *et al*., 1981; Reddy and Prasad, 1977), and Sharma and Prasad (1978) reported that the optimum dose of N for wheat could be reduced by 50 kg N ha^{-1} if slow-release fertilizer or nitrification inhibitors were used in the preceding rice crop. Higher economic returns due to neem cake coating of urea were reported by Prasad and Prasad (1980). Of late, a technique of coating urea with neem oil emulsion has been developed (Prasad *et al*., 1999b), which is being used in some urea factories in India. Thus slow-release fertilizers and nitrification inhibitors have a role in RWCS.

2. Phosphorus

In RWCS, the response to P is less marked as compared to wheat (Bhardwaj, 1978; Prasad *et al*., 1980) in the Indian subcontinent because most soils are of recent origin and their fertility buildup still continues due to fresh deposits of sediments brought by river floods. In China, however, there are large areas under red and yellow earths, which are more weathered, and on such soils rice responds well to phosphorus (Yonglu *et al*., 2000). William and Walker (1969) reported that as the soil-weathering proceeds, the amount of occluded P (Fe- and Al-phosphates) having a coating of Fe- and Al-hydroxides (oxides) increases. The increased availability of active soil P under flooded paddy conditions (De Datta, 1981) is due to the dissolution of occluded P (Patrick and Mahapatra, 1968). The increase in the availability of soil P on water logging is, however, not uniform in all soils (Mandal, 1979). It is for this reason that the same soil response to P is higher in wheat than in rice and has led to the recommendations in both India and China that if wheat is fertilized adequately, then rice can be grown on residual P (Gill and Meelu, 1983; Meelu and Rekhi, 1981 and Shihua and Wenqiang, 2000). However, Goswami and Singh (1976) analyzed data from a number of centers under the All India Coordinated Agronomic Research Project (AICARP) (Table XIII) and showed that it was not true, and the total response to P application in RWCS was the most at several centers when P was applied to both rice and wheat. Similar results were reported by Formoli *et al*. (1977) and Kolar and Grewal (1989). A national workshop on phosphorus in India also recommended an application of phosphorus to both rice and wheat in RWCS (Tiwari *et al*., 2001). From a 19-year study at Faizabad (India), Yadav *et al*. (1998) showed that in RWCS there was no response to rice or wheat in the first 5–7 years, but as the native soil P declined, the response to P increased and after 19 years it was 40 kg grain kg^{-1} P in rice and 74 kg grain kg^{-1} P in wheat. Low temperatures during wheat-growing seasons reduce the decomposition of soil organic matter and thus reduce the availability of organic P, which could be one factor responsible for the higher response of wheat to P.

Table XIII
Total Response (tons ha^{-1}) of Rice + Wheat to Application of 26 kg P ha^{-1} at Several Research Centers of AICARP in India (Data Pooled over 3 Years)[a]

		P applied to		
Experimental center	Soil	Both crops	Rice only	Wheat only
Raipur	Red and yellow	2.25	1.34	1.40
Jabalpur	Black	2.34	1.99	1.88
Kathulia farm	Red and black	2.44	2.47	1.82
Bichpuri	Alluvial	1.12	1.30	1.05
Varanasi	Alluvial	0.79	0.67	0.63
Masodha	Alluvial	1.89	1.19	1.73
Kharagpur	Laterite	1.81	1.51	0.71

[a]From Gowami and Singh (1976).

Table XIV
Relationship between Soil Test Value for P and Agronomic Efficiency of P in Rice and Wheat in India

	Agronomic efficiency of P (kg grain kg^{-1} P_2O_5)			
Crop	Low P	Medium P	High P	Reference
Rice	7	4	—	Goswami (1975)
Rice	27	21	—	Goswami (1975)
Wheat	13	10	2	Kapur *et al.* (1979)
Wheat	24	18	11	Tiwari *et al.* (1974)

Most recommendations for P application are made on the basis of Olsen's 0.5 *M* $NaHCO_3$ extractable P (available P) for neutral and alkaline soils obtained in the IGP of the Indian subcontinent. Data in Table XIV show that the response of rice to P was obtained on soils having low to medium Olsen's P, whereas the response of wheat to P was obtained even on soils analyzing high in Olsen's P. These data suggest the need for working out different limits for low, medium, and high values for Olsen's P for rice and wheat. For better predictions of the response of rice and wheat to P, the P-fixing capacity of soil should also be considered; the response to P is generally more on low P-fixing soils.

Dobermann *et al.* (1998) pointed out that the initial P flush due to submergence in rice paddies is followed by a decrease from the resorption or precipitation of Fe(ferrous)-P compounds (Kirk *et al.*, 1998; Ponnamperuma, 1972). They further pointed out that a large proportion of P taken up by rice is drawn from P pools that are soluble under alkaline, aerobic conditions

[Fe(ferric)-P and Al-P], but which are transformed into acid-soluble forms as a result of submergence and reduction (Jianguo and Shuman, 1991; Kirk and Saleque, 1995). Therefore, suitable soil tests for rice should provide an index of this pool. Skogley and Dobermann (1996) further observed that ion-exchange resins can be used to estimate bioavailable nutrients because of their low ion concentrations in soil solution; their application to rice soils has been suggested (Boruah *et al*., 1993; Turner and Gilliam, 1976; Yang *et al*., 1992). The ion-exchange resin method has also been suggested as a universal soil test for N, P, K, S, Ca, Mg, Fe, Mn, Zn, Cu, and so on.

For both rice and wheat crops it is generally recommended that P should be applied at transplanting/sowing in both India and China. However, several workers in India (Gupta *et al*., 1975; Katyal, 1978) have reported that application of 50% P at puddling and the rest at tillering (21 days after transplanting) was as effective as an application of all P at puddling. Similarly, some workers (Rana *et al*., 1978; Singh and Singh, 1979; Singh *et al*., 1980) have reported that a split application of P in irrigated wheat can be made if necessary. Thus, as compared to a nitrogen split, application of P has no advantage over a single application at transplanting/sowing. However, data available do suggest that if a farmer has failed to apply P at transplanting/sowing, the P requirements of crops can be met partially even by its application by 21 days after transplanting/sowing. In both rice and wheat, this coincides with the application of a second dose of nitrogen.

In rice the general practice is to broadcast P at final puddling, which leads to its incorporation in soil. There is really no alternative to it. Katyal (1978) suggested the technique of dipping the rice seedling roots in a P solution or slurry for saving on fertilizer P, but Meelu and Bhandari (1978) failed to find any beneficial effects of this technique. For wheat, which is mostly sown by a fertilizer-cum-seed drill in the RWCS belt, P is generally placed 3–5 cm below and to the side of the seed, which is much better than the broadcast application (Meelu *et al*., 1974; Ray and Seth, 1975). Tandon (1987) observed that extra yield of wheat brought about by deep placement of P as compared to its surface broadcast application ranges from 300 to 800 kg ha^{-1}.

Most phosphate fertilizers containing P in water-soluble form are made by reacting rock phosphate with sulfuric acid or phosphoric acid, thus requiring sulfur as a raw material. Countries such as India, which do not have their own deposits of sulfur, have tried to study the relative efficiency of nitrophosphates, which are made partly or fully from nitric acid, and ordinary or single super phosphate (SSP) and ammonium phosphate (MAP and DAP) (Prasad and Dixit, 1976; Sekhon, 1979).

In both rice and wheat, a large number of trials were conducted under the AICARP at research centers, as well as on farmers' fields during 1953 to 1969. In these trials, SSP and MAP were found to be equally effective on neutral and alkaline soils, but on acid soils, nitrophosphates also performed well (Chaudhary *et al.*, 1979; Mahapatra *et al.*, 1973; Prasad *et al.*, 1971). For wheat, Hundal and Sekhon (1980) found that nitrophosphate at Ludhiana containing more than 50% water-soluble P (WSP) was as effective as SSP, whereas at Faizabad, Yadav and Verma (1983) found that 50% WSP was optimum for wheat. For rice, 30–50% of WSP in nitrophosphates has been found to be optimum. For RWCS, Misra *et al.* (1986) concluded that 60% WSP in nitrophosphate was the best, whereas Chaudhary *et al.* (1979) found DAP and nitrophosphate to be equally effective.

Ground rock phosphate has also been tried for both wheat and rice. For wheat in neutral to alkaline soils, rock phosphate was found ineffective, but the rock phosphate–SSP mixture (1:1) was found nearly as effective as SSP (Mishra *et al.*, 1980). In rice, rock phosphate was inferior to SSP or DAP on neutral to alkaline soils (Marwaha and Kanwar, 1981), but was as effective as SSP or DAP on acid soils (Panda, 1980).

In conclusion, it may be said that for RWCS some water solubility in P fertilizers is desirable.

3. Potassium

Soils of the IGP RWCS belt in India are dominated by illite and the associated minerals are vermiculite, chlorite, quartz, feldspar, and kaolinite, whereas in the RCWS, soils in other parts of India (Maharashtra, Gujarat, and Madhya Pradesh) are dominated by smectite and associated minerals are chlorite, kaolinite, illite, allophane, quartz, and feldspar (Tiwari *et al.*, 1992). Total K in the alluvial soils of IGP ranges from 1.28 to 2.77% and exchangeable (1 *N* NH_4OAC) K contents vary from 78 to 273 mg kg^{-1} soil (Tandon and Sekhon, 1988). Thus, in general, there is sufficient exchangeable K and adequate amounts of K-bearing minerals in the IGP soils to meet the requirements of RWCS.

Soils in China practicing RWCS, however, are poor in K and adequate K fertilization is recommended for both rice and wheat (Kawaguchi and Kyuma, 1977; Shihua and Wenqiang, 2000). For 6 tons ha^{-1} wheat crop the recommended dose of K varies from 100 to 187 kg K ha^{-1} in the Sichuan province (Yonglu *et al.*, 2000). According to Islam (1995), most of the soils in Bangladesh are low in exchangeable K.

Trials on fields with high-yielding varieties of rice and wheat showed a good response to K even in the RWCS belt of IGP (Prasad and Mahapatra, 1970; Raheja *et al.*, 1970; Singh *et al.*, 1976); an application of 50 kg K ha^{-1} gave a response of 290 and 240 kg ha^{-1} of wheat and rice, respectively (Randhawa and Tandon, 1982). However, Tiwari *et al.* (1992), observed that rice tends to respond to potassium more than wheat.

Table XV
Response (kg grain kg^{-1} K_2O) of Rice and Wheat to K (60 kg P_2O_5 Over Adequate N and P) over Time in RWCS Regions of India[a]

Region	Rice 1969–1971	Rice 1977–1982	Wheat 1969–1971	Wheat 1977–1982
Humid western Himalayan	6.7	8.9	4.2	10.6
Subhumid Sutlej–Ganga alluvial plains (major RWCS belt)	4.0	5.8	2.8	6.5
Subhumid to humid eastern and southeastern uplands	3.7	8.2	1.7	5.9

[a]From Bhargava *et al.* (1985).

Table XVI
K Balance Under Different Rates of K Application after Four Cycles of Rice–Wheat Cropping Systems at Ludhiana[a]

K rate	Total K applied (kg ha^{-1})	Total K uptake (kg ha^{-1}) Rice	Total K uptake (kg ha^{-1}) Wheat	Total K uptake (kg ha^{-1}) Total	Net K balance (kg ha^{-1})	Depletion of available K[b] (kg ha^{-1})	Contribution from nonexchangeable K (%)
0	0	535	348	883	−883	34	96
25	200	563	360	931	−731	28	96
50	400	548	384	932	−532	26	95
75	600	551	404	955	−355	23	94

[a]From Meelu *et al.* (1995).
[b]From surface 0 to 15-cm layer.

The response to K on research centers in India has not been so obvious; this is due to an initial K-rich status of soils. Bhargava *et al.* (1985) showed that the response of rice and wheat to K at research centers under AICARP increased over time due to the depletion of native soil K (Table XV). In long-term experiments under PDCSR in India, a response to K in the RWCS was obtained in the 12th year on an Alfisol at Pantnagar and in the 13th year on an Entisol at Faizabad (Hegde and Sarkar, 1992). In Kanpur, Tiwari (1985) also showed that the response of both rice and wheat increased over time. This is due to a heavy depletion of K over a long period from the soils by RWCS, as shown by Meelu *et al.* (1995) at Ludhiana (Table XVI). The average depletion in exchangeable K in Kanpur district soils under RWCS was 17% (Tiwari and Nigam, 1984).

Some workers (Singh and Singh, 1978) reported that a response to K was obtained only when high levels of K and adequate P were applied

Table XVII
Response of Rice to K at Different Levels of N (Data Averaged over 6 Years)[a]

	Grain (tons ha^{-1})		
Kg N ha^{-1} (at 80 kg P_2O_5 ha^{-1})	Without K	With 50 kg K_2O ha^{-1}	kg grain kg^{-1} K_2O
100	4.14	4.38	4.9
150	4.41	4.84	5.7
200	4.14	5.15	10.1

[a]From Singh and Singh (1978).

(Table XVII), but Gangiah and Prasad (1999) and Aipe and Prasad (2001) failed to get a response to K even at high levels of K with adequate P.

The most widely used soil test method for available K is 1 *M* NH_4OAC (pH 7.0) extraction, but its suitability as a measure of plant available K remains controversial, especially when soils of different texture and clay mineralogy are considered together (Dobermann *et al*., 1998; Kemmler, 1980). This is more so due to a large contribution from nonexchangeable K (Table XVI). For lowland rice soils with a high K fixation capacity, K saturation (percentage of total CEC) is considered a better index of plant available K. On alkaline soils, which occupy about 2.5 million ha in IGP (Singh and Singh, 2001), reduced K activity in the soil solution due to preferential adsorption may contribute to low K uptake by rice even when ample K is available (Dobermann *et al*., 1998). Thus in addition to 1 *M* NH_4OAC extractable K values, other soil properties, such as clay content, nature of clay minerals, CEC, and organic matter content, need to be considered before making recommendations for K fertilization in RWCS.

Most K is applied at transplanting of rice or seeding of wheat. Lu and Shi (1982) reported that 51.8% of total K uptake in rice was during ear initiation to heading and 27.7% during grain filling and maturity. Similarly, in wheat, 69.1% of total K uptake was during jointing to ear initiation and 23.8% during flowering to maturity. This suggests a need for top dressing of K at later stages of growth of rice and wheat. A number of researchers in India (Das *et al*., 1970; Prasad and Chauhan, 2000; Singh and Singh, 1979) have shown the advantage of split application of K. According to Von Uexkull (1976), top dressing of K is advantageous (i) when the natural supply of K from soil and irrigation water decreases during later growth stages of a crop, (ii) when the soil becomes highly reduced (as in rice) and hydrogen sulfide, organic acids, Fe(ferrous), and carbonates accumulate and inhibit K uptake by crop plants, (iii) for poor tillering and late-maturing varieties, and (iv) during wet or rainy seasons. While the best time for top dressing will vary with the variety, soil type, and composition of irrigation water, application at maximum tillering and panicle initiation gives good results (Tiwari *et al*., 1992). Top dressing with K is also useful in soils subjected to leaching losses of K. Mian *et al*. (1991) reported that leaching losses in Bangladesh could be as high as 0.1 to 0.2 kg K $ha^{-1}day^{-1}$.

Because straw of rice or wheat contains most K, its incorporation or use as a mulch, as recommended in China (Shihua and Wenqiang, 2000), can help in maintaining the K status of soils. This emphasizes the need for residue incorporation in RWCS as discussed earlier.

4. Balanced NPK Fertilization

Balanced NPK fertilization in RWCS is important (Dev, 1997; Kanwar *et al*., 1972; Lian, 1989; Mohanty and Mandal, 1989; Prasad, 2000; Prasad and Power, 1994; Rattan and Singh, 1997; Tandon, 1980). Data from some research centers under PDCSR are presented in Table XVIII and these bring out the importance of balanced NPK fertilization in RWCS. The following major points emerged from these data.

Table XVIII
Change in Response to NPK over a Period of 10–12 years in RWCS at Some Centers Under AICRPCS[a]

			Control[b] ($tons\ ha^{-1}$)		Response kg grain kg^{-1} nutrients[c]					
					N		P		K	
Center	Soil	Crop	A[d]	B[e]	A[d]	B[e]	A[d]	B[e]	A[d]	B[e]
R.S. Pura	Inceptisol	Rice	1.49	1.55	20.8	7.3	18.7	28.2	−7.5	20.2
		Wheat	2.08	0.98	7.3	3.5	12.2	13.0	2.0	68.2
Pantnagar	Mollisol	Rice	3.49	1.33	3.4	7.9	4.1	7.3	8.2	6.6
		Wheat	1.07	1.19	19.3	14.3	5.1	−15.4	0.7	3.7
Faizabad	Entisol	Rice	1.01	0.82	24.2	22.0	14.2	26.4	1.5	7.0
		Wheat	0.83	0.60	21.9	17.8	17.6	33.4	12.1	3.0
Varanasi	Alfisol	Rice	3.42	1.88	7.9	15.6	10.7	10.0	6.4	14.7
		Wheat	1.35	1.00	19.6	16.5	−0.4	8.3	3.8	18.5
Rudrur	Vertisol	Rice	2.34	1.12	20.5	23.6	5.4	36.3	4.9	12.0
		Wheat	1.22	0.85	20.4	13.3	4.8	13.5	6.2	8.5

[a]Adapted from Hegde and Sarkar (1992). All India Coordinated Research Project on Cropping Systems, Modipuram.
[b]Control—no fertilizer check plot. Response to P in presence of N and to K in presence of NP.
[c]N at 120 kg N ha^{-1}, P at 35 kg ha^{-1}, and K at 33 kg ha^{-1}.
[d]Start of experiment 1977–1978 to 1980–1981.
[e]Final year for which data were collected: 1986–1987 to 1989–1990.

1. Yields of both rice and wheat without fertilizer declined over time.
2. Response of both rice and wheat to N alone declined over time, showing the need for P and K and other nutrients.
3. Response to P in the presence of N increased over time, showing a decline in the available native soil P.
4. Response to K in the presence of N and P increased over time, showing a decline in the available native soil K.

Thus in RWCS, balanced NPK (and S, discussed in the later section) fertilization is a must for sustained production.

5. Sulfur

After NPK, sulfur is the fourth plant nutrient whose deficiency is widespread in the RWCS belt in India, China, and other countries (Messick and Fan, 2000; Pasricha and Aulakh, 1997; Sakal *et al.*, 2001; Sarkar, 2000; Yadav *et al.*, 2000). The following main factors are responsible for increased S deficiency in a rice–wheat cropping system.

1. Removal of large amounts of S (25–54 kg $ha^{-1}year^{-1}$) (Yadav *et al.*, 2000c) year after year from the soil due to higher productivity of modern high-yielding varieties of rice and wheat.
2. Use of high-analysis fertilizers urea and DAP, which have replaced S-containing fertilizers such as ammonium sulfate and single super phosphate.
3. Environmental controls have reduced SO_2 emission from industries. Atmospheric SOI_2 liberated by the combustion of S-containing fossil fuels (coal, oil, and gas) is by far the greatest source of anthropogenic S emission and is the principal source of S for soils (Lefroy *et al.*, 1992). Generally the amount of atmospheric S added to soils in the rural areas of industrialized regions varies between 5 and 10 kg $ha^{-1}year^{-1}$, whereas it is only 0–5 kg $ha^{-1}year^{-1}$ in other rural areas of China (Messick and Fan, 2000).
4. In the rice–wheat belt in India, about 20–40% of the soils tested analyzed low in available S (Singh, 2001) and the same is true for China (Messick and Fan, 2000). Because organic-S is an important component of soil S, soils of the RWCS belt in India, Pakistan, and Bangladesh, which are very poor in organic matter (<0.5% organic C), are really poor in native S. The C:N:S ratio was reported to be 100:7.9:1 in Alfisols, 100:8.7:1 in Mollisols, and 100:8.5:0.5 in Inceptisols of India (Tiwari, 1995; Tripathi and Singh, 1992). Generally the C:S ratio in soils in India is about 200:1 (Singh, 2001).

Table XIX
Effect of S on Grain Yield of Rice–Wheat Cropping System[a]

Center	S applied (kg ha^{-1})	Grain yield (tons ha^{-1})	Decrease in grain yield tons ha^{-1}	%	Agronomic efficiency kg grain kg^{-1} S
Agwanpur (Bihar)	0	4.77	—	—	—
	15	5.90	1.13	24	75
	30	7.02	2.25	47	75
	45	7.68	2.91	61	65
Meerut (UP)	0	8.90	—	—	—
	15	10.11	1.20	13	80
	30	12.24	2.33	26	78
	45	11.73	2.82	32	63
Mohammedabad (UP)	0	8.40	—	—	—
	15	9.03	0.63	8	42
	30	9.80	1.40	17	47
	45	10.19	1.79	21	40
Gorakhpur (UP)	0	7.36	—	—	—
	15	7.66	0.30	4	20
	30	7.74	0.38	5	13
	45	7.90	0.60	8	13
Average	0	7.36	—	—	—
	15	8.17	0.82	11	54
	30	8.95	1.54	22	53
	45	9.39	2.03	28	45

[a]From Sarkar (2000).

Although cereals respond less to S than sugarcane, sweet potato, vegetables and oilseeds (rapeseed, peanut, soybean), and pulses, (Messick and Fan, 2000; Singh, 2001; Tandon, 1991), a good response to S has been reported for both rice and wheat (Sakal *et al*., 2000, 2001; Yadav *et al*., 2000a,c). The results of experiments conducted under TSI/FAI/IFA at four research centers on rice–wheat cropping are presented in Table XIX. In these experiments, 15–45 kg ha^{-1}S was applied to rice and its direct effects on rice and residual effects on the succeeding wheat crop were studied. The response to S application varied from 4 to 61% over no S check. In terms of kg grain kg^{-1}, it varied from 13 to 80%. In China the average response to S fertilization was 15.7 kg kg^{-1} S for rice and 13.9 kg kg^{-1} S for wheat (Messick and Fan, 2000). These and several other results from India (Tandon, 1987) and China (Messick and Fan, 2000) clearly show that S should be included in the balanced fertilizer recommendations for RWCS.

Data for S balance in rice–rice cropping system are available from China and are given in Table XX. These results show a negative balance of −6 kg S ha^{-1}year^{-1} when only NPK was applied. With the application

Table XX
Sulfur Balance as Affected by S Fertilization in Rice–Rice Cropping System in the Guangdong Province of China[a]

Treatment	Rain + irrigation (kg ha^{-1} $year^{-1}$)	Crop removed (kg ha^{-1} $year^{-1}$)	Leaching + Runoff (kg ha^{-1} $year^{-1}$)	Balance (kg ha^{-1} $year^{-1}$)
NPK	10.5	10.5	6.0	−6.0
NPK + 19.5 kg S ha^{-1} $year^{-1}$	10.5	12.0	6.0	12.0
NPK + 30 kg S ha^{-1} $year^{-1}$	10.5	15.0	6.0	19.5
NPK + manure (kg S $ha^{-1}$$year^{-1}$)	10.5	12.0	6.0	16.5

[a]From Messick and Fan (2000).

Table XXI
Recommendations for S Addition for Different Crops on the Basis of Soil Test Value (0.15% CaCl Extractable)[a]

Available S (mg kg^{-1} soil)	S fertility class	Recommended dose of S (kg ha^{-1}) for rice/wheat	Expected increase in yield (%)
<5	Very low	60	25–85
5–10	Low	45	20–50
10–15	Medium	30	5–20
15–20	High	15	1–5
>20	Very high	0	0

[a]From Singh (2001).

of S or manure, the S balance was positive (12.0–19.5 kg S $ha^{-1}$$year^{-1}$) (Messick and Fan, 2000).

Sulfur extracted by 0.15% $CaCl_2$ (Williams and Steinburgs, 1959) has been found to be well correlated to the response of crops to S (Ghai *et al.*, 1984; Shukla, 2001). With this method, a value of 10 mg kg^{-1} soil or less is considered low and a crop response to S is expected (Sarkar, 2000). Available S values, sulfur deficiency class, recommended amount of S, and expected increase in yield are given in Table XXI.

Because S requirements of crops are more at early stages of growth, generally its application at transplanting/sowing of rice/wheat is recommended. When pyrite is used as a source it should be broadcast 7–10 days before transplanting/sowing. If the S application is missed at sowing, it may be top dressed up to 20–40 days after sowing (Singh, 2001). When soil application is not made at sowing and S deficiency symptoms are seen at later stages of growth of the crop, three to five foliar applications of soluble salts of S, such as ammonium sulfate, potassium sulfate, and zinc sulfate, can be made (Singh, 2001). Soil application at sowing is the most effective method of S fertilization.

The most commonly used sources of S, along with their S contents, are single superphosphate (12% S and 16% P_2O_5); ammonium sulfate (24% S and 21% N); ammonium phosphate sulfate (15% S, 16–20% N, and 20% P_2O_5); potassium sulfate (18% S and 50% K_2O); zinc sulfate (15% S and 20% Zn); gypsum (13–20% S); elemental S (85–100% S); iron pyrites (22–24% S); phosphogypsum (11% S); and organic manure (varying content of S).

Data from several experiments in India showed that ammonium sulfate, single superphosphate, elemental S, gypsum, and pyrites were equally efficient for most crops given in divergent soil-crop management situations in different agroecological regions (Singh, 2001).

6. Micronutrients

With the adoption of modern HYV of rice and wheat and the application of high doses of NPK resulting in the removal of high amounts of micronutrients (Table XXII), their deficiencies have emerged in RWCS belts in most countries where the system is practiced. In India, a Zn deficiency was discovered first at Pantnagar (Nene, 1966) in *tarai* (forest hill) soils and then almost everywhere in the RWCS (Takkar and Randhawa, 1978). Similarly, a deficiency of iron in rice on coarse-textured alkaline soils was observed by Takkar and Nayyar (1979) and that of Mn in sandy to loam soils of Punjab for wheat in RWCS (Takkar and Nayyar, 1981). In highly calcareous soils of Bihar, Singh *et al*. (1985) reported that B deficiency is one of the constraints for sustaining high yields in RWCS. The percentages of soil samples analyzing low for different micronutrients in different states of India where RWCS is practiced are shown in Table XXIII. A deficiency of Zn is prevalent on all soils in all states. The deficiency of Fe is found to be the largest in sierozems of Haryana and lesser in Inceptisols and Entisols of Punjab and UP. Mn turns out to be the most serious constraint in coarse-textured Ustochrepts and Ustopsammants in Haryana, Punjab, and UP. A deficiency of B is most prevalent in calcareous soils of Bihar and in Entisols, Inceptisols, and Vertisols of Uttar Pradesh and Madhya Pradesh (Bansal *et al*., 1991; Dwivedi *et al*., 1993; Sakal *et al*., 1988). No Mo deficiency has yet been reported in rice and wheat. Of the various micronutrients, Zn is now included in fertilizer recommendations for the entire RWCS belt in India. Data on the removal of micronutrients by RWCS for some locations in India are given in Table XXII.

In China, Mn and Mo are required by wheat and Zn by rice (Shihua and Wenqiang, 2000). The available Mo content in all RWCS soils is low

Table XXII
Removal of Some Micronutrients (g ha^{-1} $year^{-1}$) by RWCS in India[a]

Location	Cropping system	Economic produce (tons ha^{-1})	Zn	Cu	Fe	Mn
Pusa	Rice–wheat–sorghum	5.98	606	262	4583	1238
	Rice–wheat–mungbean	4.43	445	208	4258	879
Hisar	Rice–wheat	10.10	250	190	3430	800
Pantnagar	Rice–wheat–cowpea(F)[b]	13.73	946	652	5982	1204

[a]From Rattan *et al.* (1999).
[b]Fodder.

Table XXIII
Percentage (%) of Soil Samples Deficient in Different Micronutrients in Different States of India Where RWCS Is Practiced[a]

State	Zn	Cu	Fe	Mn	B	Mo
Bihar	47	2	4	<1	31	—
Haryana	62	0.5	26	4	—	28
Madhya Pradesh	63	0.1	3	3	22	18
Punjab	47	0.1	12	2	—	—
Uttar Pradesh	64	0.4	9	6	24	—
West Bengal	9–68	—	—	—	—	—

[a]Adapted from Takkar *et al.* (1997).

Table XXIV
Average Content (mg kg^{-1}) of Selected Micronutrients in Major Soil Types of RWCS in China[a]

Soil	Zn		Mn		Mo	
	Total	Available	Total	Available	Total	Available
Red soil	177	3.0	565	120	2.43	0.14
Yellow earth	81	2.1	373	70	1.53	0.14
Purple soil	109	2.1	548	206	0.55	0.08
Limestone soil	236	1.5	2264	746	0.68	0.14

[a]From Shihua and Wenqiang (2000).

(Table XXIV), especially in arid soils where Mo is highly bound by Fe and Al oxides and is not available to crops (Li, 1983). Mn deficiency occurs in wheat only in the calcareous purple soils and light-textured alluvial soils in the upper Sichuan (Hu *et al.*, 1981). However, on acid red and yellow soils, Mn could reach toxicity levels for both rice and wheat.

Table XXV
Threshold Values of Micronutrients in Rice and Wheat Plants Under Sand/Soil[a] Culture

				Threshold values (mg kg^{-1})			
Micro nutrient	Crop	Plant part	Crop/age (days after emergence/ transplanting)	Acute	Deficient	Sufficient	Toxic
Zinc	Rice	Leaves	42–56	10	15	20	—
	Wheat	Leaves	35	10	15	20	100
Cu	Rice	Leaves	30–40	2	5	5	40
	Wheat	Top plants	35	3	4	6	—
Mn	Rice	Leaves	30–35	—	10	50	—
	Wheat	Leaves	70	7	25	60	—
B	Rice	Young leaves	48	15	20	40	50
	Wheat	Leaves	14–21	—	4	35	600

[a]From Takkar *et al.* (1989).

The DTPA extractable micronutrient test (Lindsay and Norvell, 1978) has been found most successful in India for analyses of Zn, Fe, Cu, and Mn. For hot water-soluble B, the method of Berger and Tuog (1939) is being used. For Mo, the acid ammonium oxalate procedure of Grigg (1953) is used. The critical value of DTPA extractable Zn for rice in Indian soil ranges from 0.45 mg kg^{-1} soil for alluvial sandy soil to 0.70 mg kg^{-1} soil for the calcareous soils of Bihar in the RWCS belt. A critical value for DTPA-Mn for wheat was 4.0 to 4.7 mg kg^{-1} soil in Ustochrepts and Ustiprammants of Haryana and Madhya Pradesh and a value of 3.0 mg kg^{-1} soil was observed for the alluvial soils of Punjab. Regarding B, 0.52 mg kg^{-1} soil hot water-soluble B was considered critical (Singh, 1992).

Plant tissue analysis is also used for determining micronutrient deficiencies in the RWCS belt in India, and the threshold values for different micronutrients in rice and wheat are given in Table XXV. These threshold values, determined under laboratory conditions, need confirmation under field conditions. For example, threshhold values of Zn, Mn, and B for rice are 15, 10, and 20 mg kg^{-1} leaf dry matter. These values could vary with variety, soil, and weather conditions.

a. Zinc. A soil application of 10–25 kg ha^{-1} (higher doses for heavier soils) zinc sulfate ($ZnSO_4 \cdot 7H_2O$) (21–22% Zn) is considered the best method, although dipping of rice seedlings at transplanting in 2–4% $ZnSO_4$ has been found to be quite effective (Takkar *et al.*, 1997). Studies show that a soil application of zinc sulfate may not be necessary each year or at least lower doses could be used in subsequent years. For example, in a study in Punjab, an application of 5.5 kg Zn ha^{-1} for the first four crops in the RWCS followed by 2.75 kg Zn ha^{-1} for the next 8 crops was adequate (Takkar *et al*., 1997). A foliar application of zinc (0.5% solution of zinc sulfate mixed with some lime) may be used when a deficiency is detected at a later stage in the crop.

b. Iron and Manganese. An iron deficiency is noted in upland rice or dryland rice nurseries and can be easily overcome by flooding the field or nursery bed. When the deficiency is seen in growing crops, a foliar application of a 0.5% solution of ferrous sulfate ($FeSO_4 \cdot 7HO$) (19% Fe) or Fe-EDTA solution can be used. Several sprays at 7- to 10-day intervals may be required. For soil application, a dose of 10–12 kg ha^{-1} ferrous sulfate is recommended. For manganese, a foliar application of sulfate ($MnSO_4 \cdot 4H_2O$) (26–28% Mn) mixed with lime is preferred over soil application.

It should be mentioned that Fe and Mn are present in soil in large amounts and changing the soil condition can overcome their deficiency, e.g., flooding the soils for upland rice. The addition of organic manure and green manuring can also help overcome these deficiencies.

Another alternative is to use Fe and/or Mn efficient cultivars of rice and wheat. For example, Takkar *et al*. (1997) reported that wheat cultivars HD 2329, WH542, KSM3, PBW222, and KAL1-4 were able to take up more Mn from the soil and thus are more Mn efficient.

c. Boron. For B, soil application is preferred and the sources are Borax (11% B), fertilizer borate (14% B), and boric acid (20% B); only 1–2 kg B ha^{-1} is required.

7. Integrated Nutrient Management

As already pointed out, modern high-yielding varieties of both rice and wheat are heavy feeders of plant nutrients. To meet these heavy demands of plant nutrients, farmers have mostly resorted to the use of inorganic fertilizers, and the age-old practice of applying organic manures to the farm fields has almost vanished. Because farmers mostly apply large doses of N and some P and K, their continuous application sans organic manures has created deficiencies of secondary and micronutrients, which have already been discussed. This has led to the decline in yields of rice, wheat, or both (Nambiar and Abrol, 1989; Yadav, 1998, Yadav *et al*., 1998).

Yadav (1998) reported that, on average at several locations in the PDCSR, continuous rice–wheat cropping for 16 years decreased the yield by 57% in unfertilized plots and by 32% in plots receiving N and P. Yadav *et al*. (1998) further reported that the highest rate of decline (89 kg $ha^{-1}year^{-1}$ in rice and 175 kg $ha^{-1}year^{-1}$ in wheat) was found when 120 kg

N ha^{-1} was applied. However, when balanced fertilization was practiced and 120 kg N, 35 kg P, and 33 kg K ha^{-1} were applied, the rate of decline in yield was reduced to 25 kg $ha^{-1}year^{-1}$ in rice and 62 kg $ha^{-1}year^{-1}$ in wheat.

Yadav *et al*. (2000b) also showed that at some centers there was a general decline in partial factor productivity (kg grain kg^{-1} NPK) of fertilizers over the years (11 to 14 cycles of R-W cropping), e.g., at Ludhiana it decreased from 28.3 at the start of the study (1983–1984) to 24.9 at the end of the study (1996–1997). This forces the farmers to apply more and more fertilizer over the years to get the same increase in yield as in previous years This further deteriorates soil fertility and also creates environmental problems. For example, in Punjab, there has been an increase in nitrate content in well waters due to an increased use of nitrogen fertilizer (Singh *et al*., 1995). Integrated nutrient management (INM) involving the use of organic manures, green manures, and biofertilizers to meet part of the nutrient requirement is the only way to combat the situation. Studies on the possible substitution of inorganic N by FYM or *Sesbania* green manuring were conducted under PDCSR, and some data are presented in Table XXVI, which clearly show that the same yields of rice and wheat can be obtained with a 25% substitution of N by FYM or a 50% substitution of N with *Sesbania* GM applied to rice as with a 100% of recommended dose of NPK applied to rice and wheat (Hegde, 1998a,b). In New Delhi, Misra and Prasad (2000) showed that an application of 120 kg N ha^{-1} produced 8 tons $ha^{-1}year^{-1}$ grain in RWCS. This could be achieved by *Sesbania* cowpea (*Vigna unguiculata*) GM or FYM applied to rice without any fertilizer N; with 80 kg N ha^{-1} the grain yield of RWCS could be increased to 9 tons $ha^{-1}year^{-1}$.

Information on integrated nutrient management is also available from the All India Coordinated Research Project on Long-Term Fertilizer (LTFE) scheme of the Indian Council of Agricultural Research in a number of cropping systems, including RWCS. Results from an experiment under this scheme at Pantnagar started in 1971 showed that continuous cropping of rice–wheat for 25 years reduced soil organic C from 1.48% to 0.5%, available P from 18 to 6.4 kg ha^{-1}, available K from 125 to 99 kg ha^{-1}, and available Zn from 2.70 to 0.79 mg kg^{-1}. Application of 8 tons ha^{-1} FYM to wheat each year along with 100% of the recommended NPK led to higher crop yields, restored the original organic C status, and improved the availability of P, K, Zn, Fe, Mn, and Cu in the soil (Ram, 1998). From a study conducted from 1974 to 1997 on an alkali soil at Karnal, Swarup and Yaduvanshi (1998) also concluded that an application of FYM or *Sesbania aculeate* green manuring along with a judicious application of N, P, and Zn sustained RWCS. Meelu and Rekhi (1981) and Meelu *et al*. (1994) also showed the advantage of green manuring in rice–wheat CS in Punjab.

With all the merits of FYM and green manuring, these practices have not really caught on with the farmers (Das and Biswas, 2002). With the

Table XXVI
Effect of Integrated Nutrient Management on Grain Yield (tons ha^{-1}) of Rice and Wheat at Some Research Centers Under AICRPCS in the Indogangetic Plains (IGP) of India (Average over 7–10 Rice–Wheat Cycles)[a]

Treatment (rice + wheat)	Ludhiana (Ustochrept loamy sand)			Pantnagar (Hapludoll silty clay loam)			Kanpur (Udic ustochrepts loam)			Varanasi (Aeric ochroqualfs silty loam)			Faizabad (Fluvents silt loam)			Kalyani (Fluvents clay loam)		
	Rice	Wheat	Total	Rice	Wheat	Total	Rice	Wheat	Total	Rice	Wheat	Total	Rice	Wheat	Total	Rice	Wheat	Total
Control (no fertilizer)	2.1	1.2	3.3	3.0	1.7	4.7	1.6	1.1	2.7	1.1	1.0	2.1	1.9	1.0	2.9	1.3	0.8	2.1
NPK + NPK[b]	6.3	4.5	09.8	4.7	4.0	8.7	4.0	4.6	8.6	4.0	4.0	8.0	4.3	3.3	7.6	3.5	2.6	6.1
N (50% FYM)[c] PK+NPK	5.7	4.7	10.4	4.0	3.8	7.8	3.5	4.6	8.1	3.7	4.3	8.0	4.1	3.5	7.6	3.4	2.4	6.3
N (25% FYM) PK+NPK	6.0	4.2	10.2	4.1	3.7	7.8	3.7	4.3	8.0	4.0	3.8	7.8	4.4	3.1	7.5	3.7	2.7	6.4
N (50%) GMPK + NPK	6.3	4.4	10.7	4.4	3.9	8.3	3.6	4.7	8.3	3.6	4.2	7.8	4.1	3.2	6.9	3.7	2.9	6.6
N (25%) GMPK + NPK	6.6	4.0	10.6	4.5	3.7	8.2	3.9	4.7	8.6	3.9	3.9	7.8	4.3	3.0	7.3	3.8	2.3	6.1
LSD ($P = 0.05$)	0.15	0.12		0.22	0.12		0.17	0.12		0.13	0.10		0.16	0.12		0.15	0.12	

[a]From Hegde (1998a,b).
[b]NPK (kg ha^{-1}): Rice: Ludhiana 120-131-25.2; Pantnagar 120-26.2; Kanpur 120-26.2-50.4; Varanasi 120-26.2-33.6; Faizabad 120-26.2-50.4; and Kalyani 80-21.8-33.6. Wheat: Ludhiana 120-26.2-25.2; Pantnagar 120-26.2-50.4; Kanpur 120-26.2-50.4; Varanasi 120-26.2-33.6; Faizabad 120-26.2-50.4; and Kalyani 120-26.2-33.6.
[c]Figures in parentheses indicate percentage of N supplied through FYM/*Sesbania* green manure in rice.

Table XXVII
Effect of *Sesbania* Green Manuring (GM) and Mungbean Residue Incorporation (RI) on Grain Yield and Nitrogen Uptake by Rice and Wheat in RWCS[a]

	Grain (tons/ha)				Nitrogen uptake (kg/ha) in above ground parts			
Treatment	Mungbean	Rice	Wheat	Total	Mungbean	Rice	Wheat	Total
Fallow	—	5.0	3.2	8.2	—	86.9	83.0	169.9
Sesbania (GM)[b]	—	5.3	3.4	8.6	—	108.9	88.0	196.9
Mungbean (RI)	1.3	5.3	3.6	8.9	119.6	110.6	93.7	204.3
LSD (P = 0.05)	—	0.13	0.18		—	2.90	4.85	

[a]From Sharma *et al.* (1995).
[b]Plant N incorporated in soil due to *Sesbania* GM was 78.1 kg/ha, whereas that of mungbean was 6.8 kg/ha.

mechanization of agriculture in the RWCS belt in IGP, the number of animals on the farm fields has been reduced considerably and FYM is simply not available. Similarly, green manuring has not found favor with farmers due to a lack of immediate monetary returns. Sharma *et al.* (1995) and Sharma and Prasad (1999) have therefore suggested the growing of short-duration (60 days) mungbean (*Vigna radiata*) during the summer months (May and June—the period between wheat harvest and rice transplanting), taking one picking and incorporating the legume residue before transplanting rice. This practice was found to be as effective as green manuring with *Sesbania* in RWCS and increased the productivity of the cropping system (rice + wheat) by 0.7 tons $ha^{-1}year^{-1}$ and plant N uptake by 34 kg $ha^{-1}year^{-1}$ (Table XXVII). These studies showed a fertilizer N saving of 30–120 kg N ha^{-1} in RWCS. In addition, it gives a yield of 0.5 to 1.1 tons ha^{-1} of protein-rich grain of mungbean, which is so important for a protein–malnutritioned country such as India. This practice was also as good as green manuring with *Sesbania* in preventing the decline in soil organic C as observed in plots receiving only inorganic fertilizer (Prasad and Misra, 2001). Growing of summer mungbean in RWCS was tested on the farmers' fields in Delhi during 1995–1996 and 1996–1997 (Sharma *et al.*, 2000a). In 1995–1996, N was applied at 60 or 120 kg N ha^{-1} (with 20 kg P and 4 kg Zn ha^{-1}), whereas in 1996–1997 there was only one dose of 90 kg N ha^{-1}. Wheat was grown with 40 kg N, 20 kg P, and 30 kg K ha^{-1} to study the residual effects. Incorporation of mungbean residue increased the total productivity of RWCS over summer fallow by 1.0–2.5 tons ha^{-1} at 60 kg N ha^{-1} and 0.3–2.5 tons ha^{-1} at 120 kg N ha^{-1} in 1995–1996; in 1996–1997 the increase was 0.5 to 2.6 tons ha^{-1}. In addition, 0.7-0.8 ton ha^{-1} protein-rich pulse grain was produced. The Food and Agriculture Organization

(FAO) of the United Nations has developed an IPNS model for the rice–wheat system (Roy and Ange, 1991). Using this model, it was predicted that the potential of the rice–wheat system was 11 tons ha^{-1} using 240 kg N, 39 kg P, and 100 kg K ha^{-1}. By inclusion of a short-duration legume, taking a picking of pods and incorporating its residues in soil not only produced 1 ton ha^{-1} additional protein rich grain, but also made a net savings of 30 kg N ha^{-1}.

Thus the studies in India show the advantage of applying FYM and green manuring in RWCS. A more practical alternative seems to be growing of a short-duration mungbean, taking a picking of pods, and incorporating the legume residue. This also provides the farmer with a source of income at the end of the summer season and before rice transplanting and he/she will have cash in hand to invest in rice–wheat production. Quayyum *et al*. (2001) from Bangladesh also recommended growing mungbean after wheat and before rice for a sustainable RWCS.

In addition to the contribution of *Rhizobium* through green manure/legume residue/legumes in RWCS, other biofertilizers, such as blue green algae (BGA) and azolla, have a role in rice culture and can save 20–30 kg N ha^{-1} (Bhagyaraj and Tilak, 1997; Goyal, 1993; Kannaiyan, 1993; Singh, 1997; Singh and Bisoyi, 1989; Singh *et al*., 1990a; Venkataraman, 1979), whereas *Azotobacter* can fix 10–25 kg N ha^{-1} in wheat (Pandey and Kumar, 1989). However, no reports are available on the use of these biofertilziers in rice–wheat cropping systems as a whole.

There has also been considerable research in India on phosphate-solubilizing organisms (PSO) and some of this concerns rice and wheat (Chhonkar and Tilak, 1997). The introduction of PSOs (*Pseudomonas striata*, *Bacillus polymyxa*, *Aspergillus avamori, Penicillium digitatum*, etc.) in the rhizosphere of rice and wheat (or other crops) increases the availability of P from insoluble phosphates such as rock phosphate and increases the utilization efficiency of ordinary superphosphate (Chhonkar, 1994). Inoculation of seeds or seedlings with PSOs can provide 13 kg P ha^{-1} equivalent of ordinary super phosphate (Gaur, 1990). PSOs could be useful in sustaining crop yields in RWCS when adequate P fertilization is not made.

D. Irrigation and Water Management

1. Irrigated Water Availability

In Asia, where water has always been regarded as an abundant resource, its per capita availability declined by 40–60% between 1955 and 1990; projections of the International Rice Research Institute, Manila, suggest that most Asian countries will have some water problems by the year 2025

Table XXVIII
Percentage (%) of Arable Land Under Irrigation in RWCS Countries[a]

Country	1961	1990	2000	2020
Bangladesh	5	26	32	37
China	29	45	44	45
India	15	26	29	32
Nepal	4	33	44	54
Pakistan	64	81	87	94

[a]From Gill (1994).

(IRRI, 1995). Agriculture in Asia accounts for 86% of total annual water withdrawals compared with 49% in North and Central America and 38% in Europe. Irrigated rice, in particular, is a heavy consumer of water; it takes 5000 liters of water to produce 1 kg rice, and RWCS consumes about 11,650 m^3ha^{-1} water out of which 7650 m^3ha^{-1} is by rice (IRRI, 1995).

Assured irrigation is crucial for high yields in the intensive RWCS. The total irrigated area in Asia has increased rapidly from 80 million ha in 1960 to 132 million ha in 1990, an increase of 65% (Gill, 1994). Irrigated land as a percentage of total available land in five RWCS countries is given in Table XXVIII. Pakistan has the highest percentage of irrigated land, followed by Nepal and China.

The importance of irrigation water in RWCS can be judged from the fact that Ladha *et al.* (2000) have divided the RWCS environments on the basis of the availability of irrigation water.

1. Favorable RWCS environments (FE)—areas with predominantly irrigated rice and wheat, e.g., state of Punjab in India and Pakistan and states of Haryana and western Uttar Pradesh in India.
2. Less favorable RWCS environments (LFE)—areas with predominantly rain-fed rice and irrigated/rainfed wheat, e.g., states of eastern Uttar Pradesh, Bihar, and West Bengal in India.

Yields of rice and wheat obtained under these two environments are shown in Table XXIX; yields of both rice and wheat are much higher under FE than under LFE. Furthermore, data in Table XXIX are state averages; many farmers under FE produce as much as 8–9 tons ha^{-1} of rice and 5–6 tons ha^{-1} of wheat in Punjab and Haryana. Similarly, in the Sichuan province of China, the highest yield of rice recorded was 10.6 tons ha^{-1}, whereas that of wheat was 6 tons ha^{-1} under FE (Jiaguo, 2000). Thus, under FE the total grain production for RWCS can be 14–16 tons ha^{-1}, which is very close to the potential yields of 17–18 tons ha^{-1} predicted for

Table XXIX
Wheat and Rice Yields (tons ha^{-1}) Under Favorable (FE) and Less Favorable Environments (LFE) RWCS in India[a]

States	Wheat[b]		% of wheat area under irrigation[c]	Rice[b]		% of rice area under irrigation[c]
	FE	LFE		FE	LFE	
Punjab[d]	3.69	—	96.7	4.84	—	99.1
Haryana	3.57	—	98.4	4.29	—	99.6
U.P.	2.28	2.43	92.2	3.04	2.45	60.4
Bihar	1.79	1.71	87.8	2.29	1.58	30.8
West Bengal	—	2.00	72.5	—	2.68	24.6

[a]From Ladha *et al.* (2000).
[b]1990–1993.
[c]1994–1995.
[d]Punjab and Haryana are predominantly wheat states, whereas Bihar and West Bengal are predominantly rice states. In UP, the western part is predominantly a wheat area, whereas eastern UP is predominantly a rice area.

India (Agarwal *et al.*, 2000). One reason for the higher rice yields in China is that a major part of the rice area is under hybrid rice, which produces at least 1 ton ha^{-1} more than the prevailing HYV grown in India (Vidyachandra and Gubbiah, 1997). Another reason for lower rice yields in the FE RWCS belt in India is the preference for fine grain quality such as Pusa Basmati-1, which has a yield potential of 5.5 tons ha^{-1} and covers large tracts in the states of Haryana and western Uttar Pradesh. Basmati-type rice fetches better prices in the market and overcomes the disadvantage of its lower yields as compared to hybrids and other high-yielding varieties of rice.

As regarding the source of water in India, tube wells are a major source in the FE region in western Uttar Pradesh, Haryana, and Punjab, whereas canal water is the major contributor in the LFE region in eastern Uttar Pradesh, Bihar, and West Bengal. Of late there has been great concern in India regarding overirrigation of rice and wheat in the FE region due to the free availability of water from tube wells (the electricity for agriculture is at low rates). This has created alarming changes in the water table depending on the area's hydrology. In some pockets the water table has been pushed down so much that the overall natural vegetation of the area is decreasing, whereas in other regions, the rising water table is creating salinity/sodicity. Data in Table XXX clearly show the negative water table balance in parts of Haryana and Punjab states of India. However, Jagannath (2000) pointed out that in some parts of Haryana, the water table is rising at a rate of 10–30 cm $year^{-1}$. Reasons for this include (i) seepage from the canal system,

Table XXX
Water Balance in Parts of Haryana and Punjab when RWCS Is Practiced[a]

State	District	Usable discharge (mm)	Draft (mm) (1989–1990)	Balance (mm) (1989–1990)
Haryana	Karnal	1089	1499	−410
	Kurukshetra	658	1307	−649
Punjab	Ludhiana	1264	1954	−690
	Jalandhar	703	1491	−788
	Kapurthala	334	668	−334
	Sangrur	1285	2190	−905

[a]From Joshi and Tyagi (1991).

(ii) seepage from water courses and field channels, (iii) deep percolation from irrigated rice and wheat areas as a result of overirrigation, and (iv) development of a perch water table due to an impermeable layer.

Water management in RWCS can be optimized by appropriate soil management to reduce percolation, proper scheduling of irrigation, use of the ground water, and utilization of rain water.

2. Rice

a. Soil Management Practices.

i. Puddling. Puddling is associated with rice culture in all rice-growing countries. In this process, soil is worked with water to render it less pervious; the soil particles are reoriented and noncapillary pore space is destroyed (De Datta, 1981). Bodman and Rubin (1948) observed that puddling reduced the specific volume of a silty clay loam from 1.9 to 1.2 cm^3g^{-1} in about 10 s. A puddled soil holds more water at lower potentials than in its natural state. Also, drying is slower in puddled than in nonpuddled soil. Puddling increases the bulk density of soil, reduces the hydraulic conductivity (and thereby percolation losses) and water requirement by rice (Table XXXI), reduces weeds, and eases transplanting (Sharma and De Datta, 1986. Furthermore, Singh *et al.* (2001) reported that puddling not only resulted in higher yields of rice but also of succeeding wheat over nonpuddling and saved 75 mm ha of irrigation water (Table XXXII). Similar results were reported by Samra and Dhillon (2000) from Ludhiana. Direct seeded rice has to be sown at the time of raising nursery during the hot summer months and has to be irrigated frequently.

Table XXXI
Effect of Puddling on Bulk Density and Hydraulic Conductivity of Soil and Water Requirements of Rice[a]

Treatment	Bulk density ($g\ cm^{-3}$)	Hydraulic conductivity ($10^{-4}\ cm\ s^{-1}$)	Water requirement of rice (mm)
Control	1.46	5.70	3174
Puddling	1.73	0.45	1532
Compaction	1.68	0.48	1648

[a]From Mitra and Ghosh (1989).

Table XXXII
Effect of Puddling and Method of Seeding Rice on Grain Yields of Rice and Succeeding Wheat and Irrigation Water Requirement (Means over 3 Years)[a]

	Grain ($tons\ ha^{-1}$)			Irrigation water requirement ($mm\ ha^{-1}$)		
Treatments	Rice	Wheat	Total	Rice	Wheat	Total
No puddling						
Direct seeding	3.0	3.3	6.3	1500	400	1900
Transplanting	3.6	3.5	7.1	1575	400	1975
Mean	3.3	3.4	6.7	1537	400	1937
Puddling						
Direct seeding	3.8	3.7	7.5	1475	400	1875
Transplanting	4.5	3.7	8.2	1450	400	1850
Mean	4.1	3.7	7.8	1462	400	1862

[a]From Singh *et al.* (2001a).

One or two harrowings at optimum moisture for dry tillage followed by two puddlings by a rotary puddler and planking are generally enough for a good puddle. More than half the water requirement in rice production is often used to prepare the land (including puddling) and most of it is lost through percolation. Rice soils develop cracks on drying and about 60% of water applied percolates through these cracks (IRRI, 1995).

ii. Compaction. Compaction is an alternative to puddling (Gupta *et al.*, 1981) and requires less water. It refers to an increase in the bulk density of soil using a dynamic load. Its advantages are similar to those of puddling, which include increasing bulk density, reducing the hydraulic conductivity of soils, and reducing the water requirement by the rice crop (Table XXXI).

Gupta and Woodhead (1989) reported that deep ploughing of the soil followed by compaction at optimum moisture by four to six passes of an 800-kg roller was adequate. Compaction to a 5-cm depth for rice and a 10-cm depth for wheat significantly increased the productivity of RWCS. However, this practice has yet not been adopted by farmers.

iii. Bunding. This is widely practiced by rice farmers all over the world. Bunding retains rain water. Rice farmers in several countries have permanent bunds. Because there is also much seepage loss through these bunds, many farmers plaster the bunds with mud to reduce these losses (IRRI, 1995). Bhuiyan *et al.* (1979) reported that in rain-fed rice, an increase in spillway height from 2 to 12 cm increased the depth of submergence and consequently reduced the number of water stress days during crop growth.

iv. Critical growth stages. Water use by rice crop increases with crop age and is maximum during booting to flowering when evapotranspiration (ET) is the highest. Singh and Mishra (1974) reported that a 50% depletion of available water at the panicle initiation stage reduced the yield by about 34% and that at stem elongation and tillering stages the yields were reduced by 29 and 19%, respectively. De Datta *et al.* (1975) also reported that a soil water potential of −75 cb during the vegetative stage reduced grain yield by about 1.5 ton ha^{-1}, whereas during the reproductive phase it reduced the yield by 2.5 tons ha^{-1} (over 50%). Water stress during the reproductive phase is a major factor reducing rice yields in rain-fed rice.

v. Submergence. Most rice farmers consider continuous submergence of rice fields essential for good yields, leading to overirrigation in the RWCS belt in the IGP of India. Available data suggest that flooding to field capacity throughout the rice crop considerably reduces the number of irrigations and the amount of water used. It also gives higher water use efficiency. As regarding the depth of submergence, a depth of 3–10 cm is sufficient for the optimum yield and control of most weeds (Batchelor and Roberts, 1983; Oelke and Mueller, 1969; Pandey and Mitra, 1971). Tripathi (1992) showed that 7.5 cm ponding 3 days after drying of the soil was the best water management practice for soils varying from sandy loam to clay loam (Table XXXIII). This practice gave yields that were statistically not different from those obtained with continuous ponding and reduced water and irrigation requirement, runoff, percolation, and ET. Similar results were reported by other workers in RWCS in IGP (Moolani *et al.*, 1968; Singh and Pal, 1973).

3. Wheat

Wheat in the RWCS belt in IGP is an irrigated crop. The number of irrigations given depends on the (i) growth period of wheat—less irrigation in eastern IGP where wheat matures in March–April, (ii) soil type—more on

Table XXXIII
Effect of Irrigation Practices on Grain Yield of Rice, Water and Irrigation Requirements and Runoff, Percolation, and Evapotranspiration Losses on Different Soils (Average of 2 Years) (Rainfall 648 mm)[a]

	Clay loam		Silty clay loam		Loam		Sandy loam	
Factors	A[b]	B[c]	A	B	A	B	A	B
Grain (tons ha^{-1})	6.01	5.53	6.10	5.63	6.31	5.81	5.62	4.56
Water requirement (mm)	1583	1139	1602	1220	1995	1523	2261	1806
Irrigation requirement (mm)	1125	637	1200	787	1500	975	1775	1275
Runoff (mm)	207	164	191	150	149	140	161	140
Percolation (mm)	893	569	870	599	1187	893	1515	1154
Evapo-transpiration (mm)	690	569	732	621	808	625	745	65

[a]From Tripathi (1992).
[b]Continous ponding 5±2.5 cm.
[c]7.5 cm ponding 3 days after drying of soil.

lighter soils, e.g., Psamments, (iii) rainfall received, and (iv) contribution of the water table.

Considerable research has been conducted in India on the irrigation of wheat. Earlier workers paid attention to the depth of irrigation. Singh (1945) reported that the first irrigation should be given when the soil dried to 66.75% of the field capacity by applying 7.6 cm of water. Gautam *et al.* (1966) and Raheja (1961) also suggested an irrigation depth of 6.7 to 7.6 cm. Prihar *et al.* (1978a) also pointed out that a 7- to 8-cm depth of irrigation water followed by most farmers who grow dwarf wheats was well within safe limits for loamy sand to sandy loam soils of Punjab.

Later studies involved a climatological approach (Bandyopadhyay, 1997), and the irrigation depth/cumulative U.S. Pan evaporation (ID/CPE) ratio was used for scheduling irrigation. Prihar *et al.* (1978a,b) obtained maximum wheat yields and high water use efficiency in Punjab with ID/CPE = 0.9 to 1.0 with 4.5 to 7.5 cm water from irrigation. In addition, wheat required 8–10 cm water for pre-sowing irrigation.

There have been some efforts to study soil–plant–atmospheric water relationship, CO_2, H_2O exchange of crop canopy, crop modeling, and water production functions and development of crop coefficients (K_c) of wheat (Minhas *et al.*, 1974; Kumar *et al.*, 1985; Singh and Singh, 1997). K_c values measured at Karnal for tillering, heading, grain formation, and maturity were 0.47, 1.17, 1.02, and 6.35, respectively (Tyagi *et al.*, 2000). A similar pattern in values was recorded at Pantnagar, with the maximum

Table XXXIV
Effect of Different Growth Stages on Grain Yield of Wheat (tons ha^{-1})[a]

Irrigation at	Clay loam (WT 0.4–0.8 m)	Silty clay loam (WT 0.66–1.4 m)	Loam (WT 1.8–2.4 m)
No irrigation	2.90	3.45	3.61
CRI,[b] LT, LJ, F, M	4.41	5.49	5.26
CRI	3.85	4.41	4.25
CRI, LJ	3.98	4.58	4.70
CRI, F	4.11	4.97	4.86
CRI, M	3.97	4.68	4.63
CRI, LT, F	4.21	5.11	5.10
CRI, LT, M	3.94	4.72	4.94
CRI, LJ, F	4.25	5.27	5.21
CRI, LJ, M	4.11	5.00	5.15
CRI, LT, LJ, F	4.21	5.04	5.38
CRI, LT, LJ, M	4.17	5.47	5.11
LSD ($P=0.05$)	0.58	0.61	0.41

[a]From Tripathi (1992).
[b]CRI, crown root initiation; LT, late tillering; LJ, late jointing; F, Flowering; M, milk.

being 1.00 eighty days after sowing (Agarwal *et al.*, 1977). These studies will go a long way in optimizing irrigation water in wheat. As of today, many of these findings are at the research level.

Irrigation at critical growth stages of wheat is considered the easiest approach to be adopted by farmers. Five to six growth stages have been recognized as critical for irrigation, namely crown root initiation (CRI), late tillering (LT), late jointing (LJ), flowering (F), milk (M), and/or dough (D) (Dastane *et al.*, 1974; Agarwal and Khanna, 1983). However, irrigation at a particular stage depends on the soil moisture retention capacity of the soil, depth of the water table, current soil moisture, and climatic conditions. For tall wheat grown in India before the introduction of dwarf wheat from Mexico, two to three irrigations of about 7.5 cm depth each between tillering and grain development were considered desirable (Asana *et al.*, 1958; Prashar, 1967; Singh *et al.*, 1984). For dwarf wheats introduced in India in the late 1960s and now covering most irrigated wheat in the country, CRI is considered the most important and about an 80% increase in yield due to irrigation over no irrigation is achieved by this single irrigation. In soils where the water table is 0.5 to 0.9 m deep and where some winter rains are received, this single irrigation is adequate (Table XXXIV). Thus when water is available only for a single irrigation it should be applied at CRI. If irrigation water is available for two irrigations, the recommended stages are

Table XXXV
Irrigation Timing (Days after Sowing) Based on Depth of Water Table (WT) and Soil Texture[a]

	Clay loam (WT 0.5–0.7 m)		Silty clay loam (WT 0.8–1.4 m)		Loam (WT 1.6–2.4 m)		Sandy loam (WT 2.5–3.5 m)	
Particulars	A[b]	B[c]	A[b]	B[c]	A[b]	B[c]	A[b]	B[c]
First	26	26	24	24	23	23	19	19
Second	NI[d]	NI	NI	NI	85	76	81	71
Third	NI	NI	NI	NI	NI	107	104	103

[a]From Tripathi (1992).
[b]1982–1983.
[c]1983–1984.
[d]No irrigation.

CRI and flowering. For three irrigations the recommended stages are CRI, LJ, and F. For four irrigations the recommended stages are CRI, LT, LJ, and F/M. Some data on this are presented in Table XXXIV.

The practice of submergence in rice leads to a recharge of the water table and a judicious utilization of it can save considerable irrigation water in wheat (Chaudhari *et al.*, 1974). Irrigation requirements of wheat depending on the depth of the water table in some soils are given in Table XXXV. These data show that as the water table depth increases from 0.5–0.9 to 2.5–3.5 m, the number of irrigations required in wheat increases from 1 to 3.

While adequate and timely irrigation is a must for high yields of wheat in the IGP of India and several other countries, in the middle and lower reaches of the Yangtze river, i.e., in central and southern China where 500–700 mm of rainfall may be received during the wheat-growing season, resulting in periodic water logging, adequate drainage is a necessity (Lianzheng and Yixian, 1994). Mostly an open-ditch kind of drainage system is practiced. For this purpose, 0.4- to 0.6-m-deep ditches parallel to or transverse to the length of the rice–wheat fields are provided, which are connected to 0.8- to 1.0-m-deep drainage canals surrounding the field (Fig. 6). These ditches and canals serve as drainage and irrigation channels.

E. Weed Management

Weeds are the main reason for drudgery to the farmers, especially the women who do the most of the hand weeding. In wheat, manual weeding makes up 50% of the total labor requirement. For this, more and more

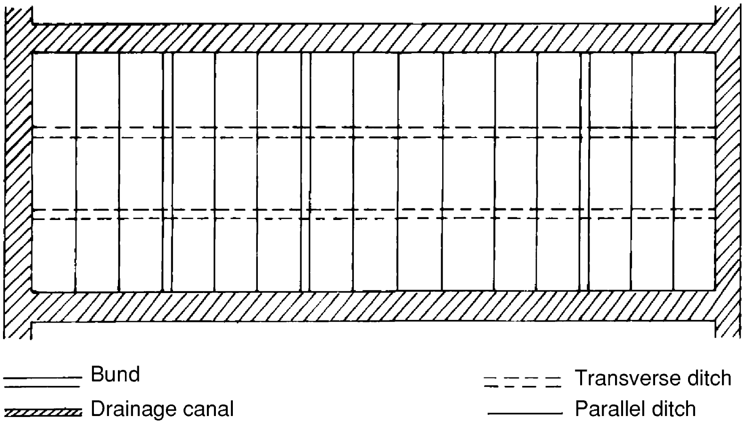

Figure 6 Plan of drainage system for wheat after rice in Nanjing, China. From Lianzheng and Yixian (1994).

farmers are turning to herbicides. The loss in grain yield due to weeds is estimated at 15–20% in transplanted rice and at 15–30% in wheat (Saraswat and Bhan, 1992).

In irrigated transplanted rice the dominant weed species in shallow depth standing water (<2.5 cm) are *Echinochloa colonum, E. crusgalli, Paspalum* spp., *Cyperus iria,* and *Fimbristylis miliaceae*, whereas with more than 2.5-cm standing water these are *Sphanoclea zeylanica, Monochoria vagenalis, Ammania baccifera,* and *Hydrolea zevlanica*. A large number of weed species for puddled transplanted rice have been listed by Pandey (1999) and these include (in addition to those already listed) *Panicum repens, Dactyloctenium aegypticum, Leptochloa chinensis, Eclipta alba, Phyllanthus niruri, Ischaemum rugosum, Caesulia axilaris,* and *Commelina benghalensis*, The dominant weed species in wheat in the RWCS belt in India are *Phalaris minor, Avena ludoviciana, A. fatua, Lathyrus apacha, Melilotus indica, Vicia sativa, V. faba, V. hirsuta, Anagalis arvensis, Chenopodium album, C. murale, Convolvulus arvensis, Euphorbia helioscopia, Asphodelus tenuifolius, Medicago denticulatus, Lipidium sativa, Trigonella polycerata, Carthamus oxycantha, Argemone mexicana, Polygonum spp., Poa annua, Lolium temulentum, Cynodon dactylon,* and *Launia* spp. (Chhokar *et al*., 2002). Of such a long list of weed species in wheat, *Phalaris minor* (canary grass) has been a major problem in continuous rice–wheat cropping over the years (Khera *et al*., 1995). The critical period of crop–weed competition for both transplanted rice and wheat is 30–45 days after transplanting/sowing (Mishra, 1997).

In addition to manual weeding and the use of push-type rotary weeders in some areas, both cultural practices and herbicides are used to control weeds in rice and wheat.

1. Cultural Practices

In rice, puddling not only controls weeds but also changes the weed flora. Grassy weeds dominate in dry seeded rice, whereas sedges and broad-leaved weeds dominate in puddle and standing water conditions. Gajri *et al*. (1999) reported that pre-puddling tillage is also beneficial in reducing weeds in rice. Cultivation of a green manure crop such as *Sesbania* before rice and ploughing it down before rice transplanting reduces weed infestation. In wheat the suggested cultural practices are cross sowing and a higher seed rate.

To overcome the increasing menaces of *P. minor,* it is suggested to change the rice–wheat CS by replacing rice or wheat in some years. Some data regarding this are presented in Table XXXVI. Changing the cropping system is strongly recommended in view of the reports of development of biotypes of *P. minor* resistant to isoproturon (Yaduraju and Singh, 1997).

2. Herbicides

For rice, a pre-emergence application of butachlor at 1.25–1.5 kg a.i. ha^{-1}, thiobencarb at 1.5–2.0 kg a.i. ha^{-1}, or anilophos 0.3 kg a.i. ha^{-1} showed good control of weeds throughout the rice-growing season (Chander and Pandey, 1996; Saraswat and Bhan 1992). Other herbicides found effective in controlling weeds in transplanted rice include nitrofen (Singh and Bhandari, 1985), oxadiazon (Brar *et al*., 1997), pendimethalin (Singh *et al*., 1990b), and propanil (Pandey, 1999). In wheat, a postemergence application of isoproturon, methabenthiazuron, metoxuron, chloroturon, or 2,4-D at 0.75 kg a.i. ha^{-1} is recommended. For pre-emergence, an application of oxyfluorfen at 0.30 kg a.i. ha^{-1} or pendimethalin at 1.0 kg a.i. ha^{-1} is recommended (Gill

Table XXXVI
Effect of Crop Diversification on Population of *P. minor*[a]

Crop rotation	Population of *P. minor* (Nos. m^{-2})	Wheat yield (tons ha^{-1})
Rice–wheat[b] (continuous for 10 years)	2350	3.0
Rice–berseem (*Trifolium alexandrinum*), rice–wheat	255	4.2
Rice–berseem, sorghum–wheat	190	4.5
Rice–potato, rice–wheat	255	4.0
Cotton–wheat[b] (for 4 years)	38	4.6
Rice–berseem, rice–berseem, rice–wheat	28	5.0

[a]From Banga *et al*. (1997).
[b]Isoproturon applied to wheat at 1 kg a.i. ha^{-1} 30–35 days after sowing.

Table XXXVII
Glyphosate and Isoproturon on the Density of *P. minor* and Wheat Yield[a]

Treatment	*P. minor* (plants m^{-2}) 60 days after sowing		Grain yield of wheat (tons ha^{-1})	
	1996–1997	1997–1998	1996–1997	1997–1998
Glyphosate (kg a.i. ha^{-1})				
0	215	98	2.76	1.12
0.6	140	90	3.07	1.71
1.25	21	65	4.31	1.87
Isoproturon (kg a.i. ha^{-1})				
0	128	118	3.40	1.74
0.75	58	46	3.73	1.82

[a]From Prasad and Yadav (2000).

et al., 1979; Mustafee 1991; Yadav *et al.*, 1986). In areas where *P. minor* and broad-leaved weeds are a problem, an application of isoproturon at 1.0 kg a.i. along with 250 g a.i. 2,4-D at 30–35 days after sowing is recommended (Dixit and Bhan, 1997).

When applied at the rate of 4 kg a.i. ha^{-1}, the butachlor residue in soil was 0.21 mg kg^{-1} soil and at lower levels no residue was detected. An application of butachlor or thiobencarb to rice up to 4 kg a.i. ha^{-1} had no harmful residual effect on succeeding wheat. Similarly, residue studies on isoproturon at 1.0, 1.2, and 1.5 kg a.i. ha^{-1} revealed that 20–40% of the chemical was lost within 30 days after application (DAA), and after 100 DAA the soil contained only 18–20% of applied chemical and by 120 DAA it was degraded to nondetectable limits (Saraswat and Bhan, 1992). Thus there are no residual effects of herbicides applied to rice on succeeding wheat or vice versa (Dixit *et al.*, 2000); therefore, recommendations for weed control for the two crops are to be made separately.

The need for effective weed control in wheat after rice was felt more with the introduction of zero-till seeding. At Modipuram (Prasad and Yadav, 2000), the zero-till plot received one irrigation after rice harvest, and glyphosate at different rates was applied after the emergence of *P. minor* (two to three leaf stage). Wheat was then sown with Pantnagar zero-till seed drill after 1 day of glyphosate application. Isoproturon was applied at 1 kg a.i. ha^{-1} 35 days after sowing. Glyphosate was very effective in controlling *P. minor* and at 1.25 kg a.i.ha^{-1} increased the grain yield of wheat by 55.9% over the control in 1996–1997 and by 95.4% in 1997–1998 (Table XXXVII). Isoproturon also controlled the *P. minor* population, but the increase in yield over no isoproturon treatment was only 9.8% in 1996–1997 and 4.5% in 1997–1998. Similarly, Singh and Prasad (2000) showed that glyphosate was quite effective in controlling grasses (including *P. minor*) as well as broad-leaved weeds in wheat fields sown by broadcast or drilled with a Pantnagar seed drill and increased the grain yield of wheat by 20 to 62%. Sulfosulfuron has also shown promise in controlling *P. minor* (Chhokar *et al.*, 2001).

IV. GENETIC MANIPULATION

As already pointed out, RWCS has gained popularity only after the introduction of HYV (high yielding varieties) of rice from IRRI, such as IR-8 and IR-36, and dwarf Mexican wheat from CIMMYT, such as Lerma Rojo and Sonora 64. Taking the lead from IRRI and the CIMMYT National Agricultural Research System (NARS) of the countries adopting RWCS have developed a large number of HYVs and hybrids of rice and wheat.

Khush (1987) suggested that the rice varieties for double-cropping situations should have the following characteristics.

i. High yielding ability
ii. Early duration
iii. Multiple resistance to diseases and pests
iv. Good grain quality
v. Tolerance for saline soil problems

These points are discussed briefly.

A. High Yielding Ability

Potential yield studies of rice and wheat by Agarwal *et al.* (1994a,b, 2000) using the ORYZAIN model for rice and the WTGROWS model for wheat showed that the potential for rice in the IGP varied from 7.2 to 11.5 tons ha^{-1}, whereas that for wheat varied from 4.75 to 8.1 tons ha^{-1}, with higher values from Punjab, Haryana, and Uttar Pradesh having a favorable environment and lower values for Bihar and West Bengal having a less favorable environment. In their simulation studies they included medium duration (130–140 days) rice varieties such as PR-106, Pusa 44, Pant Dhan 4, Sita, Saryu 52, and Saket 4. The wheat varieties included in the study were PBW 343, HD 2329, WH 542, WL 711, HUW 206, K 8804, HP 1731, and HD

2285. The potential yield may be defined as the upper limit that can be achieved by the current varieties in a no constraint environment. Thus even today there is a wide gap between the yield potential of available HYVs (6–7 tons ha^{-1} in the case of rice and 5–6 tons ha^{-1} in the case of wheat) and the theoretical potential based on environmental and physiological parameters. Thus the yield plateau in rice and wheat varieties has not yet been reached and there is scope for the development of higher yielding varieties.

The suggested desirable characters are (Pandey *et al.*, 1992):

a. Increased biomass production—selection should be made for
   - Fast leaf area development
   - Low maintenance respiration
   - Adequate growth duration (110–120 days)
b. Increased sink size—selection should be for
   - Large spikelet number per shoot
   - Larger grain size
c. Increased harvest index

The development of varieties by hybridization of selected donor parents and handling the segregating generation by different methods such as mass selection, bulk method, pedigree method, and single seed descent is known as conventional breeding. National Agricultural Research Systems (NARS) of different RWCS countries have developed a large number of varieties suiting to different situations. Some new attempts to break the yield barrier in wheat even today adopt these techniques. An example is a recent attempt in India on exploiting some local germplasms with large spikes with spikelet numbers ranging from 40 to 56 against the traditional 36–42 and 1000-grain weight varying from 45–52 as against 36 to 39 in the traditional varieties. The grain yield in these new cultivars was 667–707 g m^{-2} as opposed to 553–625 in the traditional high-yielding varieties such as PB343 and HD2329 (Singh *et al.*, 2001).

Hybrid rice occupies a large area in China (Jiaguo, 2000) and is responsible for the high productivity of RWCS in that country. The presence of hybrid vigor in rice has long been known (Jones, 1926). Because rice is a self-pollinated crop, in the absence of any cytoplasmic male sterile (CMS) and restorer lines the idea of hybrid rice did not appear feasible until Chinese rice breeders found a sterile wild rice plant in the Hunan province in the mid-1960s and developed CMS lines utilizing this wild cytoplasm (Singh, 1999). This cytoplasm was named wild abortive (WA). Utilizing this and IRRI varieties IR 24 and IR 26 as restorers, successful hybrids were developed in China that gave a 20–30% higher yield in comparison to local varieties (Lin and Yuan, 1980). The development of hybrid rice has opened up a new opportunity for developing rice hybrids for successful commercial cultivation (Swaminathan *et al.*, 1972).

A large number of hybrids have been developed in India, including APHR2 and DRRH1 in Andhra Pradesh, MGR1, COR1, and ADTRH1 in Tamil Nadu, and KRH1 and KRH2 in Karnataka (Vidyachandra and Gubbiah, 1997), UPHR-17 in UP, CNRH3 in West Bengal, and NDRH-3 in Delhi (Singh, 1999); the general yield advantage claimed is 1 ton ha^{-1}. However, rice hybrids have not yet made a dent in the RWCS belt in India, where farmers prefer to grow scented Basmati rices, which have a price premium.

The amount of efficient chemical hybridization agents (CHA) has received interest in the possibility of marketing F_1 hybrids of wheat varieties (Ganga Rao *et al*., 2000; Mahajan *et al*., 2000). In India, a research effort on hybrid wheat using CHA was initiated in 1995 (DWR 2000–2001) and 41 different molecules have been synthesized and used. Out of these, 2 have been found and tried in WH542 to further fine tune the synergistic dose. The first multiplication of a hybrid wheat trial was conducted during 2000–2001 at the Directorate of Wheat Research, Karnal; Punjab Agricultural University, Ludhiana; and CCS Haryana Agricultural University, Hisar with 19 entries and PBW 343 and HD 2687 as checks.

Mutation breeding involving ionizing radiations (X rays, gamma rays, and neutrons) and chemical mutagens (ethyle-methane sulfonate and nitrosomethyl urea) is also being attempted. One of the significant varieties developed in earlier years was that of wheat by gamma radiation and was named Sharbati Sonora (Swaminathan, 1978) in which the dark-brown color of Sonora-64 was changed to sharbati (amber), which is more acceptable to Indians.

In recent years biotechnological techniques have also been attempted in rice. Two such techniques are (1) double haploid technology (Khush and Virmani, 1985; Raina, 1989) and (2) the development of transgenics.

B. Early Duration

The short turn-around period between rice harvest and wheat sowing in the Indian subcontinent and between wheat harvest and rice transplanting in China is a serious problem. A number of studies have been made to find out the best varietal combination for the highest productivity of RWCS in different parts of India under AICRPCS; some data are shown in Table XXXVIII. In these studies, combinations of short, medium, and long duration rice varieties and wheat varieties recommended for early, normal, and late planting for different regions were compared. Results showed that a combination of medium duration rice variety and wheat variety recommended for late planting was the best for the IGP in the north. Short duration varieties of rice due to their shorter duration and

Table XXXVIII

Grain Yield (tons ha^{-1}) of Rice and Wheat Varieties of Different Durations in RWCS at Some Research Centers in India[a]

Variety duration	Kanpur			Varanasi			Faizabad			Jabalpur			Navsari		
Rice–Wheat	Rice	Wheat	Total	Rice	Wheat	Total	Rice	Wheat	Total	Rice	Wheat	Total	Rice	Wheat	Total
Short[b]–early	3.81	3.51	7.32	2.65	4.50	7.15	3.70	4.97	8.67	2.71	3.28	5.99	4.19	3.11	7.30
Short–normal	3.81	3.63	9.44	2.85	4.62	7.47	3.64	4.69	8.33	2.55	3.58	6.13	4.13	3.46	7.59
Short–late	3.81	3.93	7.74	2.83	4.83	7.66	3.68	4.89	8.57	2.31	3.33	5.64	4.11	3.39	7.50
Medium–early	5.17	3.60	8.77	3.77	4.31	8.08	5.16	4.80	9.96	2.38	3.44	5.82	4.06	2.86	6.92
Medium–normal	5.17	3.67	8.84	3.77	4.48	8.25	5.09	4.70	9.81	2.53	3.58	6.11	4.06	3.49	7.55
Medium–late	5.69	4.16	9.85	4.12	4.58	8.70	5.08	4.95	10.03	2.15	3.19	5.34	3.94	3.17	7.11
Long–early	4.42	3.35	7.77	4.33	5.21	6.54	4.21	4.37	8.58	2.99	2.19	6.18	4.64	2.86	7.50
Long–normal	4.51	3.64	4.15	2.56	4.58	7.14	4.21	4.28	8.49	2.87	3.37	6.23	4.56	3.40	7.96
Long–late	4.24	4.12	8.36	2.42	4.46	6.87	4.16	4.55	8.71	3.30	3.10	6.40	4.85	3.24	8.09

[a]From Hegde (1992).

[b]Short, 95–100 days; medium, 115–130 days; and long, 135–140 days.

long duration of rice varieties due to their maturing in cold winter days produced less rice yield and affected the productivity of RWCS. In central (Jabalpur) and western India (Navsari) the productivity of RWCS was the most when a combination of late duration rice variety and wheat variety recommended for late planting was used. Thus proper selection of rice and wheat varieties is a must for achieving high productivity of RWCS. Short duration rice varieties have a place when a catch crop (such as toria or potato) between rice and wheat is used.

However, a longer duration wheat variety may be an advantage in some situations. For example, in their zero-till studies, Mehla *et al.* (2000) reported that PBW 343 and WH 542, which mature a week later than HD 2329, gave higher yields. They pointed out that PBW 343 and WH 542 have a different phenology than HD 2329 and HD 2009. Varieties PBW 343 and WH 542 have a large vegetative phase and a short grain-filling period and are less affected by delayed sowings.

C. Multiple Resistance to Diseases and Pests

Conventional rice-growing regions are humid to subhumid and there are a large number of diseases such as blast caused by *Pyricularia oryzae*, brown leaf spot caused by *Helminthosporium oryzae*, sheath blight caused by *Rhizoctonia solani*, bacterial blight caused by *Xanthomonas oryzae*, *Tungro virus*, and Grassy stunt virus to name a few (Ou, 1985; Ramakrishnan, 1971) that take a heavy toll on the rice crop worldwide. Similarly, there are a large number of insect pests that attack the rice crop. Some important ones are brown plant hopper (BPH) (*Nilaparvata lugens*), white-backed plant hopper (WBPH) (*Sogatella furcifera*), green leaf hopper (*Nephotellix nigropictus*), rice mealy bug (*Ripersia oryzae*), rice aphid (*Hysteroneura setariae*), rice leaf folder (*Cnaphalocrosis medinalis*), rice swarming caterpillar (*Spodoptera mauritia*), rice gall midge (*Pachydiplosis oryzae*), and rice gundhi bug (*Leptocorisa varicornis*) (Atwal, 1986). Development of multiple resistance for diseases and insect pests is thus the only solution to the problem and has been pursued for quite some time (Siddiq *et al.*, 1998).

Wheat is also affected by a number of diseases such as black (stem) rust (*Puccinia graminis tritici*), brown (leaf) rust (*P. striiformis*), loose smut (*Ustilago nuda*), leaf blight (*Helminthosporium* spp.), blast (*Alternaria* spp.), and Karnal bunt (*Neovossia indica*) (Joshi, 1978; Joshi and Palmer, 1973). Important insect pests are termites (*Microtermes obesi* and *Odontotermes obesus*), Gujhia weevils (*Tanymecus indicus*), armyworms (*Pseudaletia separata*), and mites (*Petrobia latens*) (Bhatia, 1978). Development of multiple disease and pest-resistance in genotypes is a major goal of a wheat-breeding program (DWR, 2001-02).

Because rice and wheat are grown in different crop seasons having different climate parameters (temperature, rainfall, humidity), the diseases and pests in the two crops are specific to rice or wheat, and a specific breeding program for multiple resistance to diseases and pests for the RWCS has not yet been launched. A beginning has, however, been made regarding nematodes, and nematode working group partners in India, Nepal, and Bangladesh have identified *Meloidogyne graminicola, Tylenchorhynchus* spp. (*T. persicus*), *Pratylenchus* spp. (*P. thornei*), and *Hirschmanniella* spp. (*H. oryzae*) as emerging important parasites in the RWCS (Sharma *et al*., 2000c).

A detailed account of this subject is beyond the scope of this review.

D. Grain Quality

Grain quality parameters and indicators in rice and wheat vary from place to place. For example, the Japanese prefer sticky glutenous rice, whereas in the RWCS belt in IGP in India and in the entire southwest Asia the preference is for long, slender, fluffy grains with aroma that elongate and remain separate on cooking; this kind of rice is best for *biryani* or *pulao,* a dish made out of rice, vegetables, and mutton or chicken. Similarly, in wheat, *durums* with hard grains are preferred for macaroni, whereas *aestivums* with soft grains are preferred for chapati (an unleavened asian bread) making, the most popular way in which wheat is consumed in India and other countries of Asia.

In rice grain, dimensions have high heritability and are inherited quantitatively. Cross breeding of high-yielding rice varieties from IRRI, such as TN-1 and IR-8 with *basmati*-type rices, has led to the development of Pusa basmati-1 (the most popular variety in the northwest RWCS belt in India), where grain quality characters are merged with a high-yielding ability; 5 tons ha^{-1} against 1.5–2.0 tons ha^{-1} in the *basmati* type. Grain quality characters measured include length and length–width ratio in milled grain (Table XXXIX).

Table XXXIX
Grain Quality Characters in Milled Rice[a]

Designation	Length (mm)	Scale	Shape	Length–width ratio	Scale
Extra long	7.50+	1	Slender	3.0+	1
Long	6.61–7.50	3	Medium	2.1–3.0	3
Medium	5.51–6.60	5	Bold	1.1–2.0	5
Short	<5.50	7	Round	<1.1	9

[a]From Jennings *et al.* (1979).

Aroma is another characteristic in rice that has a high market value. Aromatic cultivars are found in all the three ecotypes, namely *indica, japonica,* and *javanica*. Diacetyl-1 pyrroline is the major chemical compound responsible for aroma in rice (Buttery *et al*., 1983). Inheritance of aroma has been studied by several researchers. Sood and Siddiq (1978) and Berner and Hoff (1986) have observed it to be monogenic and recessive, whereas Dhulappanvar (1976) showed from complementary genes a segregation ratio of 175 nonaromatic:81 aromatic. Suzuki and Shimokawa (1990) observed a ratio of 13 nonaromatic and 3 aromatic, indicating one dose of gene for aroma and one dose of inhibitor gene.

When the seeds of high-yielding dwarf wheats 'Sonora 64' and Lerma Rojo were imported from CIMMYT, Mexico, the major objection of the Indian consumer was their dark-brown colour and shriveled nature of grain. However, over a very short span of time Indian plant breeders were able to change the color of grains to "amber" and made them more plump by cross breeding the dwarf Mexican wheat with native Indian wheat.

In the initial years, considerable attention was given to protein content and protein quality, particularly for high lysine content in wheat genotypes (Austin, 1978). However, because there is no premium for nutritional quality in wheat in India, this line of research has not received much attention. The current thrust in *aestivums* is on chapati and biscuit-making qualities. Grain quality is also receiving considerable attention in durums where lines are being checked for semolina recovery, ß-carotene content, and grain weight. The Directorate of Wheat Research, Karnal, India, is promoting DW 1001 for the northwest plains belt. This cultivar has 12.5% protein, 6.60 ß-carotene, and a test weight of 80 g. This genotype is being registered as a genetic stock for quality and for the presence of the r-gli-45 band (DWR, 2000–2001).

E. Breeding for Special Soil Problems

In addition to nutrient deficiencies, which have already been discussed, a large proportion (about 2.8 million ha) in the IGP of India is highly alkaline ($pH > 8.5$) and contains an excessive concentration of soluble salts, a high exchangeable sodium percentage (>15), and calcium carbonate. The Central Soil Salinity Research Institute, Karnal, India, and other agricultural universities/institutes have bred varieties suitable for saline–alkaline soils. Such varieties in rice are CST7-1, Lunishree, CSRIO, CSR 5, Panvel 1, Panvel 2, Vytilla, Vytilla 3, and Vytilla 4 (Singh, 1999), whereas those in wheat are KRL 19, Raj 3077, and Job 666.

V. SUSTAINABILITY OF RICE–WHEAT CROPPING SYSTEMS

Currently there is a growing concern in sustainability of RWCS as the growth rates of rice and wheat yields are either stagnant or declining (Chand and Haque, 1998; Ladha *et al*., 2000; Paroda, 1996). An analysis of food insecurity indicators (land degradation and salinization, extent of forest cover, ground water depletion, and nature of crop rotation) in rural India carried out by the M.S. Swaminathan Research Foundation (MSSRF) with support from the World Food Program (WFP) indicates that the Punjab–Haryana region (a major part of the rice–wheat belt of India), which today serves as India's food basket, may become very food insecure in another 20 years (Swaminathan, 2002). The major issues are (1) declining yields, (2) declining factor productivity, (3) declining soil health, (4) declining water availability, and (5) disease and pest problems. The available information is discussed.

A. Declining Yields

Several rice–wheat studies at the experimental centers reported a yield decline, mainly for the rice crop (Duxbury *et al*., 2000; Nambiar, 1995; Regmi, 1994; Yadav, 1998). Duxbury *et al*. (2000) showed that 8 out of 11 long-term rice–wheat experiments, which had run for more than 8 years, showed a decline in rice yield over time, whereas only 3 centers showed a decline in wheat yield. Of the 7 long-term rice–wheat experiments examined by Ladha *et al*. (2000), none had a significant yield decline in wheat, but rice yields at Pantnagar in long-term fertility experiments in India declined at a rate of 2.3% year^{-1}; the rice yield decline of 2.7% year^{-1} at Ludhiana was not statistically significant. An analysis of yield trends in 30 long-term rice experiments with rice–rice or rice–wheat conducted in seven countries (China, India, Indonesia, Bangladesh, Vietnam, the Philippines, and Malaysia) covering a wide variety of soil types by Dawe *et al*. (2000) suggested that yield declines are not very common, particularly at yield levels of 4–7 tons ha^{-1}.

Ladha *et al*. (2000) pointed out that some of the variation in yield, however, may be related to changes in variables other than those associated with sustainability. Process-based models have been tried for RWCS by combining various approaches (Timina *et al*., 1995, 1996, 1998). IBSNAT/IFDC-based CERES-rice and CERES-wheat models and Wageningen-based ORYZA-1 and WHEAT-W models using data sets from Pantnagar, India, and Nashipur, Bangladesh, confirmed yield decline over time.

Table XL
Grain Yield of Rice and Wheat in Five RWCS States of India and Their Annual Growth Rate[a]

	Grain yield (tons ha^{-1})				Annual growth rate (%)	
State	1972	1975	1985	1995	1972–1985	1985–1995
			Rice			
Punjab	1.95	2.30	3.11	3.34	4.0	0.9
Haryana	1.71	1.79	2.58	2.58	3.7	0.8
Uttar Pradesh	0.79	0.86	1.35	1.82	3.1	3.3
Bihar	0.90	0.87	1.06	1.33	−0.8 NS[b]	0.9 NS
West Bengal	1.22	1.20	1.53	2.07	0.5	3.3
			Wheat			
Punjab	2.29	2.32	3.09	3.99	2.6	2.3
Haryana	1.95	1.76	2.72	3.66	2.7	3.3
Uttar Pradesh	1.26	1.17	1.33	2.42	3.7	6.4
Bihar	1.34	1.28	1.59	2.07	0.5	2.8
West Bengal	2.15	2.02	2.48	2.32	0.0	0.8 NS

[a]From Kumar *et al.* (1998).
[b]Not significant.

Research centers, however, provide good agronomic management and may not really reflect the happenings at the farmers level. Economists have therefore used state average yields over years as a parameter to check on the yield trend. Chaudhary and Harrington (1993) reported that expansion of the rice and wheat area in Haryana had halted and that the growth of rice productivity had slowed down.

Analyzing yield data of rice and wheat from five states of India (Table XL), Kumar *et al.* (1998) observed that only in Punjab and Haryana there was a lower growth rate in rice yields, and only in Punjab was there a slight decrease in the growth rate of the wheat yield. It should be mentioned that the rice and wheat yields are the highest in Punjab and Haryana, and thus a declining growth rate during 1985–1995 could be due to some areas already reaching the yield potential of the varieties present before 1985.

Results of yield data analysis from Bangladesh, Nepal, India (five states), and Pakistan for two time intervals, namely 1970–1985 and 1985–1998, are given in Table XLI. In Bangladesh there was a decline in the growth rate of yields of both rice and wheat. One factor affecting yields was the import of wheat from the United States, Australia, and Canada under the food-aid program, providing disincentives to wheat growers in Bangladesh (Ladha *et al.*, 2000). In Nepal there was a higher growth rate from rice and wheat in the 1985–1998 period as compared to the 1970–1985 period. Regarding the

Table XLI
Growth Rates (% year^{-1}) of Rice and Wheat Yields in Three Countries and Five States of India[a]

	Rice		Wheat	
Country/states	1970–1985	1985–1998[b]	1970–1985	1985–1998[b]
Bangladesh	2.03	1.99	7.71	0.75
Nepal	−0.16	1.49	1.76	2.16
India				
West Bengal	1.20	2.66	0.58	2.09
Bihar	0.69	2.28	1.42	2.89
Uttar Pradesh	3.64	3.35	3.75	1.97
Punjab	3.61	0.66	2.88	1.97
Haryana	3.42	0.70	3.05	2.33
Pakistan	0.71	1.51	2.58	2.06

[a]From Ladha *et al*. (2000).
[b]1995–1997 data for the states of India.

five states of India where RWCS is practiced, the trend was the same as in the analysis by Kumar *et al*. (1998).

Thus the yield data analysis for RWCS countries in south Asia indicates that yield decline is not universal. In regions where such declines are recorded, the causative factors could be other than sustainability and need to be found.

B. Factor Productivity

Factor productivity is the ratio of output and input in a production system. When only one input factor, such as fertilizer N, is taken into consideration, it is termed partial factor productivity (PFP) and generally a subscript is given to indicate the input. For example, PFP for nitrogen is written as PFP_n (Prasad *et al*., 2000). When an entire fertilizer is taken into consideration, it is written as PFP_f. PFP is easy to determine on the basis of field experimental data. However, total factor productivity (TFP) takes into consideration all the factors that go into production, e.g., land, seed, labor (human and animal), machinery, fertilizer, manure, pesticides, irrigation, and interest on capital input, and is therefore a more complicated exercise.

Yadav (1998) studied PFP_n from field experimental data from four research centers in India, and data are shown in Table XLII. Over a period of 16 years there was a decline in the PFP_n at three centers in the case of rice but only at 2 centers in the case of wheat. Mean values showed a decline of PFP_n in rice but not in wheat. Apparently the main factor was a decline in

Table XLII
Partial Factor Productivity (PFP_n) (kg Grain kg^{-1} N) for Rice and Wheat in RWCS at Start and After 16 Years of RW Cropping at Four Research Centers in India[a]

Research center	Starting year	After 16 years	% change
	Rice		
Pantnagar	42.4	25.6	−39.6
Faizabad	38.6	41.0	6.2
Sabour	35.8	14.5	−59.5
Rewa	39.7	18.3	−53.9
Mean	39.1	24.8	−36.7
	Wheat		
Pantnagar	17.3	45.1	160.7
Faizabad	34.2	29.3	−14.3
Sabour	24.8	14.5	−41.5
Rewa	15.8	19.8	25.3
Mean	23.0	27.2	32.5

[a]From Yadav (1998).
[b]N applied at 120 kg N ha^{-1} to rice and wheat with 35 kg P and 33 kg K ha^{-1}.

Table XLIII
Trends in Indices of Factor Productivity (TFP) of RWCS in Punjab, Haryana, and Uttar Pradesh States of India[a]

	TFP (%)			Annual growth rate (%)		
State	1976[b]	1985	1992	1976–1985	1985–1992	1976–1992
Punjab	75.8	97.9	103.1	3.2	0.8	1.9
Haryana	84.2	103.7	103.9	2.4	−0.1 NS[c]	1.4
Uttar Pradesh	99.3	128.4	120.1	2.2	−1.2	1.6

[a]From Kumar *et al.* (1998).
[b]Average figures for the triennium ending the year given.
[c]Not significant.

yield over years at some of their centers. Although not familiar with these calculations, farmers in Punjab, Haryana, and the UP (western) state of India have, over the years, increased their N application rates to rice.

Kumar *et al.* (1998) studied the trends in TFP of the RWCS in the three states of India (Punjab, Haryana, and UP) and their data are shown in Table XLIII. These data clearly show a lower annual growth rate in TFP during 1985–1992 as compared to that during 1976–1985; in Uttar Pradesh, the TFP growth rate during 1985–1992 was negative.

Factor productivity studies in India thus show that the sustainability of RWCS is certainly questionable, at least in some regions. Socioeconomic factors, including the price policy of the governments, could play a key role in making RWCS sustainable.

C. Soil Health

1. Chemical Properties

Data from the AICRPCS on organic C, available P, and available K are reported in Table XLIV, whereas those on available Zn, Cu, Mn, and Fe are reported in Table XLV. After 7–10 cycles of RWCS there was a decline in organic C and available P from initial data at two out of three centers, whereas in the case of available K, there was a decrease from initial data at all three centers. However, when NPK fertilization was done, there was an increase in organic C from initial data at Ludhiana and Faizabad, but not at Kanpur. Application of part N through FYM or GM further increased organic C in the soil, with the increase being more with FYM than with GM. Balanced NPK fertilization increased available P at all the three centers, and the increase was more when FYM was applied because additional P was applied with FYM. The available K in soil, however, did not reach the initial level even with NPK fertilization with or without FYM or GM. This shows that depletion of K from soil was more than its application. Available Zn, Cu, Mn, and Fe were studied only at Faizabad and there was a decrease from initial data in the control as well as in the NPK fertilized plots with or without FYM or green manure. This again shows that a depletion of Zn, Cu, Mn, and Fe was more than its addition in RWCS. Several other studies in India (Brar *et al*., 1998; Meelu *et al*., 1994; Sharma and Prasad, 1999; Sharma *et al*., 1995, 2000; Yadav and Kumar, 1998) reported an increase in organic C due to the addition of organic residues. Thus RWCS leads to a decline in soil organic C unless adequate fertilization and organic residue addition are practiced. Bronson *et al*. (1998) suggested that the degradation of soil organic matter is faster in rice–wheat than in rice–rice soils.

Ladha *et al*. (2000) pointed out that soil organic C depletion may not be the only effect of rice–wheat cropping over a long period of time, but that the nature of the chemical composition of organic matter may also change. In continuously flooded rice–rice systems, Olk *et al*. (1996) showed an increase in phenolic compounds in soil organic matter, and preliminary studies indicate that this may also be happening in RWCS soils.

From a 3-year study at New Delhi, Prasad and Misra (2001) showed that an increase in soil organic C in a short span of time may not be noted but that the addition of fertilizer N and legume residues certainly increases

Table XLIV

Effect of Integrated Nutrient Management on Organic C, Available P, and Exchangeable K in Soil After 7–10 Cycles of RWCS at Different Centers under AICRPCS in the IGP of India[a]

	Organic C (%)			Available P (0.5 *M* $NaHCO_3$ extracted) P (kg ha^{-1})			Available K (1 *N* ammonium acetate extractable) K (kg ha^{-1})		
Treatments	Ludhiana	Kanpur	Faizabad	Ludhiana	Kanpur	Faizabad	Ludhiana	Kanpur	Faizabad
Initial	0.33	0.40	0.37	11.2	11.2	13.8	101	348	355
Control (no fertilizer)	0.36	0.13	0.23	7.8	12.4	7.6	92	122	277
NPK+NPK[b]	0.42	0.32	0.39	25.0	15.1	20.4	96	151	290
N (50% FYM)+NPK	0.48	0.30	0.51	35.5	18.1	19.4	99	172	305
N (25% FYM)+NPK	0.44	0.20	0.45	28.8	11.6	22.0	99	192	292
N (50% GM)+NPK	0.46	0.38	0.46	21.3	13.5	17.9	92	175	293
N (25% GM)+NPK	0.45	0.30	0.45	15.3	10.6	19.0	92	145	281

[a]From Hegde (1998a,b).
[b]Treatment details as in Table XXVI.

Table XLV
Effect of Integrated Nutrient Management on Micronutrient Status of Soils at Faizabad (India) after 12 Cycles of RWCS[a]

	Available (DTPA extractable) micronutrients (mg kg^{-1} soil)			
Treatment	Zn	Cu	Mn	Fe
Initial	2.02	2.40	12.6	17.0
Control (no fertilizer)	0.86	1.06	7.8	10.8
NPK+NPK[b]	0.71	0.95	7.9	12.0
N (50% FYM)+NPK	1.07	1.10	9.2	14.0
N (25% FYM)+NPK	0.94	1.13	8.9	13.1
N (50% GM)+NPK	0.98	1.13	10.5	19.2
N (25% GM)+NPK	0.96	0.99	9.0	17.5

[a]From Yadav and Kumar (1998).

available (alkaline permanganate oxidizable) N in soils, which was more after the wheat harvest than after the rice harvest. Thus addition of fertilizer N and legume residues definitely increases the labile-N pool [the term suggested by Dudal and Deckers (1993)]. Glendining and Powlson (1995) also reported that application of 144 kg N ha^{-1} to winter wheat at Broadbalk for 122 years caused only a 20% increase in Kjeldahl soil-N but a 60% increase in mineralizable N.

Thus while it is generally accepted that continuous RWCS over a long period of time without the addition of organic manures does bring about a decline in soil fertility; detailed information on different plant nutrients is yet not available. Data on temporal variations in soil organic C and available plant nutrients in RWCS are not at all available, but are necessary because of the widely different microenvironments in which rice and wheat are grown.

2. Physical Properties

A number of studies have been done on the effect of puddling practiced while preparing land for rice transplanting on physical properties of soil. Destruction of large size aggregates and dispersion of particles by puddling result in their rearrangement, leading to a massive plastic mud of reduced porosity and higher moisture retention, which is the goal of puddling (Sharma and De Datta, 1986). Puddling of silty clay loam at Pantnagar converted 61.7% of the water-stable aggregates of a diameter greater than 0.5 mm into smaller fractions and

Table XLVI
Effect of Crop Residues in Bulk Density (g cm^{-3}) of Soils in RWCS[a]

	1996–1997	1997–1998		1998–1999	
Treatment	After wheat	After rice	After wheat	After rice	After wheat
Legume residue					
Fallow	1.58	1.54	1.61	1.51	1.49
Sesbania	1.50	1.47	1.47	1.46	1.40
Mungbean	1.49	1.46	1.43	1.44	1.41
LSD (P=0.05)	0.09	0.05	0.10	0.05	0.02
Wheat residue					
No residue	1.53	1.45	1.56	1.48	1.47
Residue	1.52	1.52	1.46	1.46	1.39
LSD (P=0.05)	NS	NS	0.09	NS	0.01

[a]From Sharma *et al.* (2000).

reduced the mean weight diameter from 1.7 to 0.69 mm (Tripathi, 1992). Puddling in a sandy loam soil decreased larger aggregates of 20–50 mm from 30 to 17% and of larger than 50 mm from 20 to 2% (Gupta and Woodhead, 1989). However, a puddle soil becomes harder on drying and again forms larger clods with large size aggregates. Gupta and Woodhead (1989) reported that ploughing three times on puddled rice fields after rice harvest increased the aggregates of 50 mm from 3 to 43%. Thus there is a desirable change of aggregate sizes from the puddled rice soil when wheat is grown. The destruction in soil structure as judged by aggregate size distribution by puddling does not affect wheat production adversely. Singh *et al.* (2001) reported higher yields of wheat in puddled rice plots as compared to direct seeded rice plots.

Puddling of soil for rice cultivation increases the bulk density of soil in RWCS. The bulk density of 15- to 22- and 25- to 32-cm layers of a silty clay loam soil planted to wheat after rice increased from 1.40 to 1.50 and 1.48 to 1.58 g cm^{-3}, respectively (Tripathi, 1992). This increase in bulk density in the rice–wheat sequence can be reduced by the incorporation of crop residues (Table XLVI).

The effect of a 9-year rice–wheat–cowpea sequence in long-term experiments at Pantnagar (Tripathi, 1992) showed that the hydraulic conductivity of a 0- to 10-cm layer in rice plots with 100% NPK was 0.230 cm h^{-1}, whereas that in a 25- to 32-cm layer was 0.012 cm h^{-1}; the corresponding values for a fallow plot were 0.86 and 0.04 cm h^{-1}. Similarly, Sur *et al.* (1981) reported that the hydraulic conductivity of a 5.25-cm layer of a sandy loam soil under RWCS was only 33–55% of that under maize–wheat.

Thus the aforementioned and several other studies on soil physical properties have centered around the effects of puddling in rice fields. What is needed is information on the temporal changes in soil physical properties in RWCS on different soils and to relate these to the sustainability of RWCS.

D. Pest Problems

Rice–wheat cropping regions fortunately have fewer disease and pest problems than rice–rice systems, with the latter being practiced in higher humidity and temperature conditions conducive to the growth of disease and pest-causing organisms. Nevertheless, there are disease and pest problems in the RWCS belt, some of which have emerged due to the introduction of rice in this nontraditional rice belt in India. Some pests, such as canary grass (*Phalaris minor*), have emerged in wheat in northern India only after the introduction of rice (Saraswat and Bhan, 1992).

A survey conducted by Savary *et al.* (1997) in the RWCS belt in Uttar Pradesh, India, showed that mean yield losses due to weeds could be 13%, whereas the yield loss due to insect damage (dead hearts) could be 9.2%. Brown spot and sheath blight emerged as important diseases and losses could be 9.6 and 6.4%, respectively (Table XLVII). Of course, in the case of serious attack by any pest, the damage could be 27.3 to 69.5%.

Table XLVII
Yield Loss Estimates Due to Different Pests in RWCS in Uttar Pradesh, India[a]

	Mean yield loss		Maximum yield loss	
Injury	Absolute (tons ha^{-1})	Relative (%)	Absolute (tons ha^{-1})	Relative (%)
Weed infestation above the rice crop canopy	0.30 ± 0.06	6.2 ± 1.2	2.77	55.2
Weed infestation below the rice crop canopy	0.34 ± 0.07	6.8 ± 1.4	2.54	52.6
Dead hearts (*Scirpophaga incertulas*)	0.46 ± 0.07	9.2 ± 1.4	2.63	52.4
Brown spot (*Helminthosporium oryzae*)	0.33 ± 0.03	6.6 ± 0.6	2.43	48.4
Sheath blight (*Rhizoctonia solani*)	0.32 ± 0.06	6.4 ± 1.2	3.49	69.5
Sheath rot (*H. sigmoideum*)	0.02 ± 0.02	0.4 ± 0.4	0.12	2.4
Neck blast (*Pyricularia oryzae*)	0.06 ± 0.02	1.2 ± 0.4	1.37	27.3
All injuries	1.43 ± 0.27	28.5 ± 5.4	—	—

[a]From Savary *et al.* (1997).

VI. SOCIOECONOMIC AND POLICY FACTORS

Studies on the effect of socioeconomic and policy factors on the productivity of RWCS have not been studied. One measure of socioeconomic factors is the amount of fertilizer consumed in a region. In the IGP RWCS belt, all the districts of Punjab and 80% of the districts in Haryana consumed more than 100 kg NPK ha^{-1} $year^{-1}$ as compared to UP and Bihar, where the figures was only 49 and 40%, respectively (Table XLVIII). This showed up in the productivity of RWCS, as shown by the state average yields of rice and wheat in these states. The identification of constraints, which include fewer per capita income and less availability of credit, will go a long way in augmenting RWCS yields.

As regarding government policies, the procurement of rice and wheat at preannounced prices by the government of India for the public distribution system (PDS) has been the major driving force in augmenting the production of RWCS, which in some states has spread at the cost of other crops, particularly grain legumes (Kumar *et al.*, 1998), which were generally grown on marginal land.

Similarly, import of a large quantity of wheat (1.0–1.5 million tons $year^{-1}$) as food aid from wheat surplus donor countries such as the United States, Australia, and Canada in Bangladesh could have depressed the prices of wheat in the local market and provided disincentives to the growth of wheat production (Ladha *et al.*, 2000). Information generated on costs and returns shows that boro rice has higher financial and economic returns than wheat; this encouraged rice–rice over rice–wheat cropping systems.

Table XLVIII
Number of Districts Consuming More Than 100 kg NPK ha^{-1} $year^{-1}$ and Average Yields of Rice and Wheat During 1998–1999 in RWCS States in IGP in India[a]

	Districts consuming more than 100 kg NPK ha^{-1} $year^{-1}$		State average yield (tons ha^{-1})	
State	Number	% of total districts in the state	Rice	Wheat
Punjab	17	100	3.15	4.33
Haryana	16	89	2.24	3.92
Uttar Pradesh	41	49	1.96	2.41
Bihar	22	40	1.30	1.99

[a]From FAI (1999–2000).

Thus government policies and socioeconomic factors have an impact on RWCS. More detailed studies on these aspects are suggested.

VII. FUTURE RESEARCH NEEDS

1. Detailed information is needed on the decline in yield/partial factor productivity (PEP)/total factor productivity (TFP) to demarcate the regions where it is happening and diagnostic surveys are required in these areas to find out the causes for such declines so that ameliorative measures can be taken.
2. Information on the temporal availability of plant nutrients in RWCS is urgently required, especially for the plant nutrients that undergo oxidation–reduction cycles such as nitrogen, sulfur, iron, and manganese. Oxidation–reduction of Fe and Mn also affects the availability of P. No information is available on the effect of seasonal variation of submergence to well-drained conditions on the availability of these and other plant nutrients.
3. Studies are needed on the rate of decomposition of cereal and legume residues under rice- and wheat-growing conditions and how they affect the development of soil organic matter (SOM). The changes that SOM undergoes under such divergent physicochemical and environmental conditions are hardly understood. The highest yields of rice and wheat being obtained on soils with the lowest SOM in India is a myth that needs to be solved. Is it total agronomic management or something related to soil management? These studies will permit a better integrated nutrient management policy.
4. Development of better soil and plant analysis techniques are needed for a better prediction of the soil nutrient-supplying capacity of soils to permit more reliable fertilizer recommendations.
5. Simpler and better methods are needed for scheduling irrigation in rice and wheat to save each drop of water. Strategies need to be developed to prevent farmers from overirrigating rice.
6. Plant breeding research using modern techniques and biotechnology is needed to develop (a) high-yielding short-duration rice and wheat varieties suitable for different agroecological conditions, (b) high-yielding wheat varieties for late planting in RWCS, and (c) high-yielding rice and wheat varieties suitable for saline/sodic soils.
7. There is a need to develop disease and pest forecasting models for different agroecological zones where RWCS is practiced.
8. A rice transplanting machine suitable for transplanting conventionally grown rice seedlings of 25–50 days of age is still a dream. Growing small

seedlings on plastic or PVC mats for which machines are available is not the general practice in RWCS.

9. Better machines for direct seeding of wheat after rice need to be developed.
10. Detailed socioeconomic studies are needed to determine the factors limiting the productivity of RWCS and to advise the government(s) on policies that will assure good economic returns to farmers practicing RWCS.

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