POTASSIUM NUTRITION OF THE RICE–WHEAT CROPPING SYSTEM

Bijay-Singh,[1] Yadvinder-Singh,[1] Patricia Imas,[2]
and Xie Jian-chang[3]

[1]Department of Soils, Punjab Agricultural University,
Ludhiana 141 004, India
[2]International Potash Institute-Coordination India, c/o DSW,
P.O. Box 75, Beer Sheva 84100, Israel and
[3]Nanjing Institute of Soil Science, Chinese Academy of Sciences,
71 Beijing East Road, Nanjing 210008, People's Republic of China

Among the cropping systems commonly followed in the Indo-Gangetic plain of South Asia and in China, rice-wheat cropping system occupies more

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than 26 M ha of cultivated land and removes the highest amount of potassium. To a large percentage of area under rice-wheat cropping system, particularly in the Indo-Gangetic plains, very little or no potassium fertilizers are being applied and thus most of it comes from potassium reserves of the soil. Each harvest leaves the soil poorer with respect to potassium. Imbalance in the use of nitrogen, phosphorus and potassium is further creating situations, which may lead to reduced sustainability of the rice-wheat cropping system. Whereas illite is the dominant potassium bearing clay mineral in soils in the Indo-Gangetic plains, clay minerals in soils under rice-wheat system in China are at a more advanced stage of weathering than illite so that responses of both rice and wheat to applied potassium are substantial in China. Response of sequentially grown rice and wheat to applied potassium is influenced by time and method of application of different sources of potassium and interaction of potassium with other nutrients. Issues pertaining to sustainability of rice-wheat system have been examined in terms of potassium fertility of soils, mineralogy and forms of soil potassium, long-term potassium balances and changes in soil potassium. In spite of potassium incorporation through irrigation, crop residues and fertilizers, the occurrence of negative potassium balance in soils in the Indo-Gangetic plains has serious implications on mineralogy of potassium in soils in terms of advancement of weathering front in illite-vermiculite or illite-vermiculite-smectite phases. In China, most of the soils under rice-wheat system are already in kaolinite and vermiculte-smectie phases and thus application of potassium leads to increased yields of both rice and wheat. Substantial potassium applications will have to be made to sustain high production levels of the rice-wheat cropping systems and to avoid further advancement of weathering front of potassium bearing minerals in the soil.

I. INTRODUCTION

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) grown sequentially in an annual rotation constitute a rice–wheat cropping system. In annual cycle, suitable thermal conditions for both rice and wheat exist in warm-temperate and subtropical areas and at high altitudes in the tropics. The rice–wheat rotation is one of the world's largest agricultural production systems, occupying more than 26 Mha of cultivated land in the Indo-Gangetic Plains in South Asia and in China. It accounts for about one-third of the area of both rice and wheat grown in South Asia and its production provides staple grains for more than one billion people, or about 20% of the world's population. Irrigated rice–wheat cropping systems have remained the major source of the marketed surplus of food grain for feeding the growing urban population in South and East Asia.

From 1960 to 1990, genetic improvements leading to development of highly fertilizer responsive rice and wheat varieties and improved management strategies resulted in a dramatic rise in productivity and production from rice–wheat systems. Both rice and wheat are exhaustive feeders, and the double cropping system is heavily depleting the soil of its nutrient content. A rice–wheat sequence that yields 7 t ha^{-1} of rice and 5 t ha^{-1} of wheat removes more than 300 kg nitrogen, 30 kg phosphorus, and 300 kg ha^{-1} of potassium from the soil. Even with the recommended rate of fertilization in this system (straw taken out of the fields), a negative balance of the primary nutrients still exists, particularly for nitrogen and potassium. The system in fact, is now showing signs of fatigue and is no longer exhibiting increased production with increases in input use. Evidence of declining partial or total factor productivity is already becoming available (Hobbs and Morris, 1996). Causes for this decline include changes in biochemical and physical composition of soil organic matter, and a gradual decline in the supply of soil nutrients causing macro- and micronutrient imbalances due to inappropriate fertilizer applications (Ladha *et al.*, 2000). Depletion of soil potassium seemed to be a general cause of yield decline in 23 rice–wheat long-term experiments in the Indo-Gangetic plains investigated by Ladha *et al.* (2003).

Before the advent of high yielding varieties of rice and wheat or when increasing areas were brought under a rice–wheat system, indigenous sources could supply appreciable quantities of nutrients. For example, irrigation and flood water provided significant amounts, particularly where erosion is active. This was the case during early years of irrigation schemes, as in China (Greenland, 1997), and continues on the flood plains of large rivers such as Jamuna and Meghna of Bangladesh (Whitton *et al.*, 1988). Although in several rice–wheat areas where ground water is used for irrigation, potassium inputs may be more than 30 kg ha^{-1} $year^{-1}$ (Pasricha, 1998), yet importance of potassium nutrition of rice–wheat systems stems from two facts: (1) the removal of potassium by above-ground plant parts and losses through leaching far exceeds the small additions through fertilizers and manures and it should have serious implications on the sustainability of the system on a long-term basis; and (2) lack of balanced availability of nitrogen, phosphorus, and potassium to rice and wheat that may hinder achieving the potential yields (Bijay-Singh and Yadvinder-Singh, 2002). Balanced application of nitrogen, phosphorus, and potassium means replenishing the soil potassium reserves which are being continuously mined by following high intensity rice–wheat cropping sequence. As exhaustion of potassium influences mineralogical transformations in soils, potassium nutrition of rice–wheat cropping systems is also important in terms of defining quality of the soil to be transferred to future generations. We have attempted to address these issues in this chapter and discussed potassium nutrition of sequentially grown rice and wheat in China and the Indo-Gangetic plains of India, Pakistan, Bangladesh and Nepal in terms of producing high yields from this system and maintenance of soil fertility on sustainable long-term basis.

II. THE RICE–WHEAT CROPPING SYSTEMS

A. Distribution

In the Indo-Gangetic plains, rice–wheat cropping systems are spread over a vast area spanning from Punjab in Pakistan in the west to the Brahmputra flood plains of Bangladesh in the east (Fig. 1). More than 85% of the rice–wheat system practised in South Asia is located in the plains of the Indus and Ganges, conveniently divided into four transacts. The trans-Indo-Gangetic plains occupy large areas of Punjab in Pakistan and Punjab and Haryana in India. Upper and middle Indo-Gangetic plains comprise the areas of western-central and eastern Uttar Pradesh, Bihar, and the *Tarai* in Uttaranchal in India and in Nepal. The *Tarai* belt is an extension of the Indo-Gangetic plains and has an altitude of 100–200 m above mean sea level. The lower parts of the Indo-Gangetic plains are located in West Bengal in India, and parts of Bangladesh (Fig. 1). In more than 10 Mha in India occupied by rice–wheat systems, about 23% of the total rice area produce wheat and approximately 40% of the wheat area produce rice (Table I).

In China, the rice–wheat systems are located primarily in the Yangtze river basin around 30° ± 4°N latitude (Zheng, 2000; Huke *et al.*, 1993c) and are widely practised in the provinces of Jiangsu, Zhejiang, Hubei, Guizhou, Yunnan, Sichuan and Anhui (Fig. 1) (Timsina and Connor, 2001). Although most

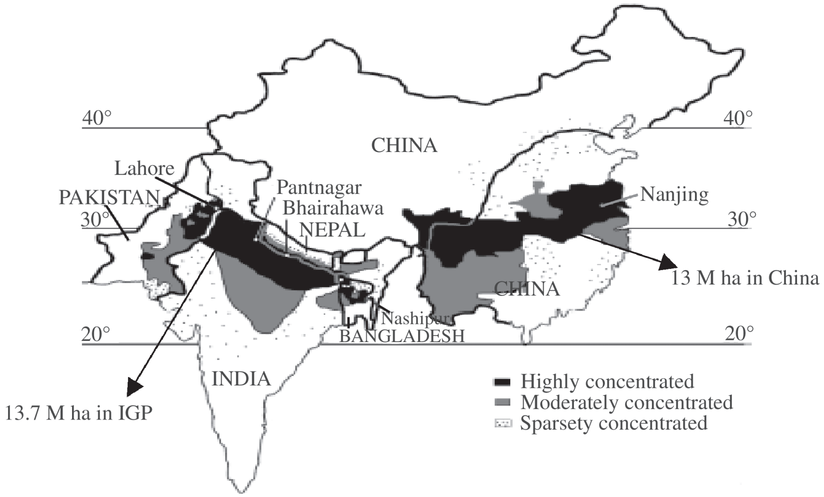

Figure 1 Distribution of rice–wheat production areas in South Asia and China. The curve passing from northeast to southwest China represents the limits for growing rice–wheat sequences in China. [adapted from Timsina and Connor (2001); based on data from Huke and Huke (1992); Huke *et al.* (1993a,b,c); Woodhead *et al.* (1993, 1994)].

Table I
Area Under Rice–Wheat Systems in the Indo-Gangetic Plain and China, and Contribution of Rice Plus Wheat to Total Cereal Production and Total Caloric Intake in Different Countries

		Area (%)		Contribution (%)	
Country	Area (Mha)	Rice	Wheat	Total cereal production	Total national caloric intake
China	13.0	31	35	72	56
India	10.3	23	40	85	60
Pakistan	2.3	72	19	92	62
Bangladesh	0.5	5	85	100	94
Nepal	0.6	35	84	71	63

Based on data from Singh and Paroda (1994); Aslam (1998); Yadav *et al.* (1998)
Source: Timsina and Connor (2001).

rice–wheat cropping systems are found below 35°N latitude in the plains and below 28°N in the highlands, these are also located as far as 40°N across the Huihe and Yellow rivers (Lianzheng and Yixian, 1994; Zheng, 2000).

Out of total area of 26 Mha under rice–wheat cropping system, around 13, 10 and 2.2 Mha are located in China, India and Pakistan, respectively (Table I). Proportion of the total rice or wheat areas also varies considerably in different countries. Rice and wheat together contribute 70–100% of total cereal production and 56–94% of the national calorie intake in China and South Asian countries in the Indo-Gangetic plain (Table I). Since good lands are being diverted to other sectors of national economies, the prospects for further expansion of the rice and wheat area seem remote (FAO, 1999). Additional sources of productivity growth in rice–wheat would have to come through enhanced overall system productivity.

B. CHARACTERISTICS

In the trans- and western parts of the upper Gangetic plains, rice–wheat system mostly includes an indica-type monsoon rice and a spring wheat, because there is generally insufficient time for a third crop. In the eastern part of the upper Gangetic plains, and in the middle and lower Gangetic plains, where temperatures are generally higher, the rice–wheat systems often include an additional crop (such as mungbean, cowpea, jute) after wheat or before rice. In the *Tarai* of Nepal, a rice–rice–wheat cropping system is also followed.

The Indo-Gangetic plains have a continental monsoonal climate. In the northwest trans-Gangetic plains, the average annual precipitation ranges from 400 to 750 mm year^{-1} and increases toward the warm and humid parts of the lower Gangetic plains of West Bengal and Bangladesh, where annual rainfall is as high as 1800 mm $year^{-1}$. Nearly 85% of the total precipitation is received during the warm humid/subhumid monsoon season from June to September when rice is grown. In winter months, only a few showers are received from December to February. The weather is cool and dry during November to March when wheat is grown. The Indus plain drains into the Arabian Sea, whereas the Gangetic plains gradually slope from the northwest towards the Bay of Bengal. There are wide variations in soil types, generally coarser in the trans- and upper Gangetic plains and becoming finer with the run of the river systems. Soils are primarily calcareous and micaceous alluviums with sandy loam to loam in the upper reaches becoming finer textured in the distal plains close to the mouth of the river systems (Gupta *et al*., 2002). Irrigated (and partially irrigated) and rainfed agriculture co-exist in several districts. This has led to a mosaic pattern of agricultural development in the Indo-Gangetic plains. Most soils in the Indo-Gangetic plains are deficient in nitrogen. Deficiency of phosphorus is next in order of importance. Because of the micaceous nature of soils, deficiency of potassium is starting to emerge in several areas (Ladha *et al*., 2002).

In China, the growing season for wheat is shorter in the south (early November to mid-May) than in the north (early October to mid-June). Thus, longer duration wheat cultivars are combined with shorter duration rice cultivars of japonica type during the cool dry winter in northern China. In southern and southeastern China, farmers grow a second rice crop in the rice–wheat system and sweet potato replaces the second rice crop in southeastern and southwestern China (Timsina and Connor, 2001). Whereas the average productivity of the rice crop in China ranges from 6.0 to 8.2 t ha^{-1}, wheat yields are 2.1–3.2 t ha^{-1} (Gupta *et al*., 2002). In regions where the rice–wheat system is practised in China, annual precipitation varies from 650 to 1400 mm, increasing from the south to southeast. Most precipitation is received during April and October. The annual total sunshine hours are more in the river plains (about 2000 hr) than in the plateau region in the south or in southeastern China (1100–1400 hr). In the plateau region, red earths are low in soil fertility. In the valley and low mountainous regions, purple earths are fertile soils (Gupta *et al*., 2002).

The two crops in rice–wheat cropping systems have contrasting edaphic requirements. Wheat is grown in upland well-drained soils having good tilth, whereas rice is commonly transplanted into puddled soils and prefers continued submergence. Thus, a dominating feature of the rice–wheat cropping system is the annual conversion of soil from aerobic to anaerobic and then back to aerobic conditions. Flooding of rice fields causes several chemical and biochemical changes in the soil, which regulate transformations and availability of nutrients (Ponnamperuma, 1972; 1985; Cao and Hu, 1995). The flooded soil is characterized by larger amounts of exchangeable potassium and sodium compared with the upland soil, particularly in the cultivated layer (Zhang, 1985). Submerged soils differ from others in the control of acidity and alkalinity because the partial pressure of CO_2 in flood water buffers carbonate and lowers pH. The pH changes alter chemical equilibria and consequently the availability of different nutrients. However, most chemical changes are reversible on draining, which suggests important implications for nutrient management in rice–wheat systems.

III. POTASSIUM FERTILIZER USE IN THE RICE–WHEAT CROPPING SYSTEMS

Data pertaining to application of potassium fertilizers to rice and wheat in China and in the four countries of the Indo-Gangetic plains are given in Table II. Although the data for the two crops do not necessarily pertain to when these are sequentially grown in an annual rotation, the data do provide a fairly good estimate of the extent of potassium fertilization. While on average more than 25 kg ha^{-1} of potassium is being applied to both rice and wheat in China, the range in the Indo-Gangetic plain is 0.4–8.3 kg ha^{-1}. However, to a large percentage of area under rice–wheat system, particularly in the Indo-Gangetic plain, no potassium fertilizer is being applied. In Bangladesh, application of potassium amounts to only 27% of the total removal by rice–wheat cropping systems (Saunders, 1990).

Table II
Potassium Fertilizer Use in Rice and Wheat in China, India, Pakistan, Bangladesh and Nepal

	Area (Mha)	Fertilizer potassium use[a] (kg ha^{-1})	Fertilizer potassium consumption (×10^3 Mt)
China (1997)			
Rice	30.17	33.2	600.8
Wheat	28.98	26.6	76.9
India (1998)			
Rice	43.45	7.8	253.4
Wheat	26.70	3.2	74.9
Pakistan (1999)			
Rice	2.42	0.4	0.2
Wheat	8.33	5.1	0.6
Bangladesh (1998)			
Rice	10.12	8.3	84.0
Wheat	0.88	6.6	5.9
Nepal (1989)			
Rice	1.43	0.8	0.5
Wheat	0.60	1.7	0.4

Source: IFA, IFDC, IPI, PPI and FAO (2002); IFA, IFDC and FAO (1999).

[a] To calculate average fertilizer potassium use, the area under rice and wheat receiving no potassium fertilizers was not taken into account.

In the Indo-Gangetic plains in India, the general recommendation for rice is to apply 25 kg ha^{-1} of potassium in Punjab (trans-Gangetic plains) and up to 50 kg ha^{-1} in the middle and lower Gangetic plains (Uttar Pradesh and West Bengal). For wheat, the range for potassium application is 21–58 kg ha^{-1} (Tiwari, 2000). Diagnostic surveys (Yadav *et al.*, 2000b) have indicated that rice–wheat farmers in the Indo-Gangetic plain seldom adopt recommended fertilizer doses and potassium fertilizers are rarely used. Fertilizer use pattern for rice–wheat systems in the Indo-Gangetic plains varies greatly from one part to another. For example, in out of 36 districts in Punjab and Haryana states in northwestern India, 34 districts consumed more than 100 kg ($N + P_2O_5 + K_2O$) ha^{-1}. On the other hand, 95 out of 155 districts of the eastern part comprising Uttar Pradesh, Bihar and West Bengal consumed 100 kg ($N + P_2O_5 + K_2O$) ha^{-1} or less. While fertilizer nitrogen remained heavily subsidized, reduction in subsidies of phosphate and potash in India adversely affected their consumption. This resulted in continued imbalance in fertilizer use (Yadvinder-Singh and Bijay-Singh, 2001b). In 1998, the $N:K_2O$ ratio was wider in northwestern states of Punjab (45.2) and Haryana (171.5) consuming the highest amount of fertilizer per unit area as compared to in eastern states (11.5 and 3.2 in Bihar and West Bengal, respectively) of the Indo-Gangetic plain (Fertiliser Association of India, 1999). Thus, the highest amounts of potassium fertilizers are being applied in West Bengal followed by Bihar, Uttar Pradesh, Punjab, and Haryana. The percentage of total potassium fertilizer applied in the summer season when rice is grown was, however, in reverse order—highest in the Punjab and lowest in West Bengal. In China too, fertilizer use is highly imbalanced in favor of nitrogen. For example, in 1993 the $N:K_2O$ ratio for fertilizer consumption was 8.3:1 (Xie, 1995). In rice–wheat cropping systems in South China, a monitoring of 10 sites for 10 years revealed that on average while organic sources contributed 89 kg K ha^{-1}, contribution of chemical fertilizers was only 38 kg K ha^{-1} (Wang *et al.*, 2002).

IV. POTASSIUM FERTILITY OF SOILS UNDER RICE–WHEAT CROPPING SYSTEMS

Total potassium in alluvial soils of the Indo-Gangetic plains in India ranges from 1.28 to 2.77%; the range for exchangeable potassium contents is from 78 to 273 mg K kg^{-1} soil (Tandon and Sekhon, 1988). Soils in the Indus plain in Pakistan contained 2.65–3.55% K (Zia and Rahmatullah, 1998). In large tracts of tropical and subtropical soils of China supporting rice–wheat cropping systems, total potassium varied from 1.06 to 2.02% (Cao and Hu, 1995). Although soils under rice–wheat systems contain large amounts of potassium as an essential part of their matrix, many times the soil fails to supply adequate amounts of the nutrient to meet the normal needs of the plant. Even two soils that contain the same amount of total potassium reserves and water soluble potassium may differ widely in their behavior in supplying the needs of the plants. Potassium fertility of soils can be defined better by understanding the mineralogy of soil potassium, forms of potassium, and different kinds of potassium transformations occurring in the soil.

A. MINERALOGY OF SOIL POTASSIUM

Potassium feldspars and micas are the potassium minerals present in the soils of Indo-Gangetic alluvial plains in India (Sidhu, 1984). Potassium feldspar species present in these soils are microcline and orthoclase. Mica minerals present are muscovite and biotite in the coarser fractions and illite in the finer fractions. Illite, a mixed layer mica-monmorillonite, is partially weathered muscovite mica with layer charges less than for muscovite; part of its charge originates in the octahedral layer, unlike the muscovite. Sand fractions are dominated by quartz, micas, and feldspars in decreasing order (Sidhu and Gilkes, 1977; Kapoor *et al.*, 1982; Pundeer *et al.*, 1978). The silt fraction resembled the sand fraction in mineralogical makeup. Illite, vermiculite, and different amounts of smectite, chlorite, and kaolinite are common clay minerals. The illites are predominantly dioctahedral (Kapoor *et al.*, 1981; 1982; Sidhu and Gilkes, 1977).

Soils in western and central Uttar Pradesh (Upper Gangetic plain) have illite and chlorite as the dominant clay minerals (Ghosh and Bhattacharya, 1984). *Tarai* soils contain largely illite and chlorite but also some mixed layer minerals, kaolinite and quartz. In western Uttar Pradesh, smectite was found to be the dominant clay mineral along with illite, chlorite, kaolinite, quartz, feldspar, and allophane. The salt affected alluvial soils in the Indo-Gangetic plain were found to contain smectite–mica and chlorite–vermiculite interstratified minerals. In the lower Gangetic basin, illite or smectite are the dominant minerals in the soils. Mishra *et al.* (1996) found that whereas smectite–illite–chlorite is the most common clay mineral phase in the terraces, soil clays of flood plains are dominated by an illite–smectite–chlorite phase in the middle and lower Gangetic plains.

Sekhon *et al.* (1992) carried out a systematic study of mineralogical composition of silt and clay fractions in soil samples collected from eight soil series in the rice–wheat regions in the Indo-Gangetic plain in India. The results of this study as described in Table III reveal that except in two series from lower Gangetic plains in West Bengal, illite is the dominant clay mineral in the seven soil series spread over the states of Punjab, Uttar Pradesh, and Bihar. Dominant minerals in the silt fraction in the entire Indo-Gangetic plain are quartz–feldspar, quartz–mica or quartz alone (Table III).

In Pakistan, containing the western part of the Indo-Gangetic plains, soils under rice–wheat systems contain large amounts of mica (about 50%) in sand and silt fractions and illite (about 50%) in clay fractions (Akhtar and Jenkinson, 1999). Besides illite, the clay fraction contained kaolinite, montmorillonite, chlorite, and vermiculite (Bajwa, 1989). These soils experience moderate levels

Table III
Mineralogical Composition of Clay and Silt Fractions in Soil Samples Collected from Rice–Wheat Growing Regions of the Indo-Gangetic Plains in India

	Clay fraction		Silt fraction	
Soil series and location[a]	Dominant mineral	Associated mineral	Dominant mineral	Associated mineral
Nabha (Ludhiana, Punjab)	Illite	Vermiculite, chlorite, quartz, feldspar, kaolinite	Quartz, mica	Vermiculite, feldspar
Khatki (Meerut, Uttar Pradesh)	Illite	Chlorite, vermiculite, quartz, feldspar, kaolinite	Quartz	Mica, vermiculite
Akbarpur (Etah, Uttar Pradesh)	Illite	Smectite, vermiculite, chlorite, kaolinite, quartz, feldspar	Quartz, mica	Vermiculite, feldsapr
Rarha (Kanpur, Uttar Pradesh)	Illite	Vermiculite, chlorite, quartz, feldspar, kaolinite	Mica, quartz	Vermiculite, feldspar
Jagdishpur Bagha, (Muzaffarpur, Bihar)	Illite	Chlorite, smectite, quartz, feldspar	Quartz, mica	Feldspar, chlorite, vermiculite, 2:1–2:2 intergrades
Raghopur (Muzaffarpur, Bihar)	Illite	Chlorite, smectite, quartz, feldspar	Quartz	Mica, feldspar, chlorite, vermiculite, 2:1–2:2 intergrades
Hanrgram (Bardhaman, West Bengal)	Smectite, Illite	Vemiculite, kaolinite, quartz, feldspar, chlorite	Quartz	Mica, vermiculite, feldspar
Kharbona, Birbhum, West Bengal	Kaolinite	Illite, smectite, quartz, feldspar	Quartz	Mica, vermiculite, feldspar, kaolinite

Source: Sekhon *et al*. (1992).

[a] Listed in order of location from trans- to lower Indo-Gangetic plains.

Table IV
Potassium-supplying Potential of Major Soil Groups in China

Category	Slowly available K[a] (mg K kg^{-1} soil)	Predominant clay minerals	Major soil groups
Very low	<66	Kaolinite	Latosols and laterite red earths and their paddy soils
Low	66–166	Kaolinite, hydrous micas	Red earths, yellow earths and their paddy soils
Moderate–low	166–332	Vermiculite, kaolinite	Paddy soils in Taihu Lake and Zhujiang River valleys, sandy soils alongside the Changjiang River
Moderate	332–498	Hydrous micas, vermiculite, kaolinite	Alluvial paddy soils in Dongting Lake and Gan River valleys, yellow brown earth, sandy fluvo-aquic soil, brown earths
Moderate–high	498–747	Hydrous micas, vermiculite (chlorite)	Purplish soils, castanozems, and meadow soils
High	747–1162	Hydrous micas, montmorillonite	Dark brown earths, chernozem, cinnamon soil, and clayey fluvo-aquic soils
Very high	>1162	Hydrous micas	Grey desert soil, brown desert soil

Source: Xie *et al.* (1982, 1990).
[a] K extractable with 1*M* HNO_3.

of weathering of provenance K-minerals as a large amount of applied K^+ gets fixed (Ranjha *et al.*, 1992).

The mica content in the rice–wheat continuous cropping area in China is about 14% (Li *et al.*, 1992). Predominant clay minerals present in seven categories of soils in China classified on the basis of potassium-supplying potential are listed in Table IV. The soils in regions where the rice–wheat cropping system is commonly practised in China fall into the categories of low to moderate–high potassium supplying potential (Xie *et al.*, 1990). Thus, kaolinite and vermiculite are the dominant clay minerals in red earths, yellow earths and their paddy soils, paddy soils in Taihu Lake and Zhujiang River valleys, and in sandy soils alongside the Changjiang River. On the other hand, alluvial paddy soils in Dongting Lake and Gan River valleys, yellow brown earth, sandy fluvo-aquic soil, brown earths and the purple soils derived from purple sandstone mostly distributed in Sichuan and other provinces in subtropical wet regions in South China contained hydrous micas as the dominant clay mineral and thus highest potassium-supplying potential as based on 1M HNO_3 extractable potassium.

Depending upon climate, vegetation, and drainage, minerals continue to weather and proton-exchange constitutes an important means for potassium release from micas. The degraded micas thus formed acquire inter-layer space from which more potassium can be released over time. However, if application of potassium fertilizer increases the concentration of potassium in soil solution, K^+ may enter expanded inter-layer spaces and become fixed by reversing the weathering process. Since a hydrated form of Ca^{2+}, the dominant cation in the solution of most soils under rice–wheat systems in the Indo-Gangetic plain, is larger than K^+, it enlarges the interlayer space releasing more K^+ in the process. When plant roots remove potassium from the soil solution, more potassium continues to be released from the clay minerals by cation (including proton) exchange. The gradual release of potassium from positions in the mica lattice results in the formation of hydrous mica (6–8% K) or illite (4–6% K). Further release of potassium due to weathering, including excessive mining by rice–wheat cropping systems, converts illites to transitionary clay minerals (2–3% K) such as expanding illites and inter-stratified minerals and ultimately leads to formation of montmorillonite/vermiculite (<1% K).

B. FORMS OF SOIL POTASSIUM

Soil potassium is often considered to exist in solution, and in exchangeable and non-exchangeable (fixed and structural potassium) forms. The amount of solution and exchangeable potassium is usually a small fraction of total potassium (1–2% and 1–10%); the bulk of soil potassium exists in potassium-bearing micas and feldspars (Sekhon, 1995). The amount of potassium present in the soil solution is often smaller than the crop requirement for potassium. Thus continuous renewal of potassium in the soil solution for adequate nutrition of high yielding varieties of rice and wheat is obvious. Similarly, the exchangeable potassium component has to be continuously replenished through the release of fixed potassium and weathering of potassium minerals. Hence, potassium nutrition of crops is a function of the amounts of different forms of potassium in soil, their rates of replenishment and the degree of leaching.

Brar and Sekhon (1986) studied four loam soils from Indo-Gangetic alluvium and found that desorption of potassium by electroultrafiltration (EUF) differed considerably, although the soils tested similarly for exchangeable potassium. Thus, for a given amount of exchangeable potassium, one soil may supply more potassium to plants than another. In general, illite dominant soils have a larger proportion of water soluble to exchangeable potassium than smectite dominant soils. Sekhon *et al.* (1992) determined different forms of potassium in samples collected from eight well-defined benchmark soil series in the Indo-Gangetic plain of India. The water soluble potassium content in the soil varied from 14 to 31 mg K kg^{-1} (Table V). Exchangeable potassium content was influenced by the clay

Table V
Forms of Soil Potassium in Samples Collected from Eight Soil Series in Rice–Wheat Growing Regions of the Indo-Gangetic Plain in India

	Water soluble K		Exchangeable K[b]		Non-exchangeable K[c]		
Soil series and location[a]	(mg kg^{-1})	% of total	(mg kg^{-1})	% of total	(mg kg^{-1})	% of total	Total K (%)
Nabha (Ludhiana, Punjab), Udic Ustochrept, pH 7.7–9.8	27	0.10	57	0.22	1334	5.05	2.64
Khatki (Meerut, Uttar Pradesh), Typic Haplustalf, pH 7.2 –8.7	14	0.05	70	0.26	1548	5.73	2.70
Akbarpur (Etah, Uttar Pradesh) Udic Haplustalf, pH 7.7–9.8	14	0.07	55	0.28	1330	6.68	1.99
Rarha (Kanpur, Uttar Pradesh), Udic Ustochrept, pH 8.1–8.8	15	0.05	67	0.24	1856	6.75	2.75
Jagdishpur Bagha (Muzaffarpur, Bihar), Typic Ustifluvent, pH 7.8–9.4	26	0.14	39	0.22	1923	10.62	1.81
Raghopur (Muzaffarpur, Bihar), Aquic Eutrochrept, pH 7.8–9.0	31	0.12	53	0.20	2200	8.46	2.60
Hanrgram (Bardhaman, West Bengal), Veric Eutrochrept, pH 5.0–5.9	18	0.15	87	0.71	601	4.89	1.23
Kharbona (Birbhum, West Bengal), Typic Haplaquept, pH 4.5 –6.8	18	0.51	27	0.77	98	2.80	0.35

Source: Sekhon *et al*. (1992).

[a] Listed in order of location from trans- to lower Indo-Gangetic plains.

[b] 1M ammonium acetate extractable potassium minus water soluble potassium.

[c] 1M boiling HNO_3 extractable potassium minus 1M ammonium acetate extractable potassium.

mineralogy of the series. The soils from Punjab, Uttar Pradesh and Bihar with illite as the dominant clay mineral contained 39–70 mg K kg^{-1}. But the two soils from West Bengal with smectite (Hanrgram) and kaolinite (Kharbona) as the dominant clay minerals contained 87 and 27 mg K kg^{-1} exchangeable potassium, respectively. Effect of clay mineralogy was also very striking in influencing the non-exchangeable potassium content of the soils in the Indo-Gangetic plains. The two soils from West Bengal contained only 601 and 98 mg K kg^{-1} non-exchangeable potassium, whereas all the remaining six soil series with illite as the dominant clay mineral showed very high content of non-exchangeable potassium varying from 1330 to 2200 mg K kg^{-1}. Trends in total potassium content were also similar to that for non-exchangeable potassium; minimum potassium contents were observed in soils from West Bengal in the lower Indo-Gangetic plains.

Different forms of potassium in tropical and subtropical soils in China are listed in Table VI. Rice–wheat systems are practised in red soil, yellow soil, yellow brown earth, purple soil, and paddy soil. The weathering intensity of these soils decreased in the order: red soil > yellow soil > yellow brown earth > purple soil and thus potassium content of these soils also increased in the same order (Cao and Hu, 1995). Purple soils mostly distributed in Sichuan province possessed the highest potassium-supplying and buffering capacity. However, soils under rice–wheat systems in China contained conspicuously less

Table VI
Forms of Soil Potassium in Samples Collected from Tropical and Subtropical Soils Developed on Different Parent Materials in China

Soil	Parent material	Total K (%)	Non-exchangeable K[a] (mg K kg^{-1} soil)	Water soluble and exchangeable K[b] (mg K kg^{-1} soil)
Latosols	Basalt	0.20	37	55
	Sea deposit	0.31	44	44
Lateritic red earth	Granite	0.38	64	65
Red soil	Red clay	0.95	163	66
	Granite	2.72	198	76
Yellow soil	Arenaceous shale	1.06	75	98
Yellow brown earth	Arenaceous shale	1.28	362	80
Purple soil	Arenaceous shale	2.02	483	132
Paddy soil	Sediment	1.68	224	124
	Alluvial deposits	1.43	314	82
	Lake deposits	1.71	685	173

Source: Cao and Hu (1985).
[a] 1M HNO_3 extractable K.
[b] 1M Ammonium acetate extractable K.

exchangeable, non-exchangeable or total potassium than in soils in the Indo-Gangetic plains of South Asia. As shown in Table IV, the clay mineralogy of Chinese soils is also in accord with the magnitude of different forms of potassium in the soils. The potassium content of paddy soils also varied widely depending upon parent material (Table VI).

C. POTASSIUM TRANSFORMATIONS IN SOILS

Dynamic equilibrium reactions occurring between different forms of potassium have a profound effect on the potassium nutrition of rice–wheat cropping systems. The direction and rate of these reactions determine the fate of applied potassium and release of non-exchangeable potassium. Under certain conditions, added potassium is fixed by the soil colloids and is not readily available to plants.

The most important aspect of the potassium transformations in soils under rice–wheat cropping systems is the rate at which the non-exchangeable portion is released to the exchangeable and soluble forms. The rate and magnitude of release are primarily dependent on the level of potassium in the soil solution and the type and amount of clay minerals present (Martin and Sparks, 1985; McLean, 1978). The rate of release of non-exchangeable potassium is also influenced by the degree of exposure of edges of clay mineral to the soil solution, and the position of non-exchangeable potassium with respect to outer edges. Thus in some soils, the rate of release of non-exchangeable potassium may be slow enough to restrict yield, whereas it may be rapid enough to meet the potassium needs of the entire crop. Sekhon *et al.* (1992) studied release kinetics of non-exchangeable potassium using the hot HNO_3 method as described by Pieri and Oliver (1987) in samples from eight well-defined benchmark soil series in the Indo-Gangetic plain of India. An estate of step-K was also obtained by repeated extractions with boiling 1M HNO_3 at 10-minute intervals, using a soil solution ratio of 1:10 (Haylock, 1956). The data are listed in Table VII. Kaolinite-dominant alluvial soils (Kharbona) and smectitic acidic alluvial soils (Hanrgram) in the lower Gangetic plain showed lower rates of potassium release from the non-exchangeable fractions than the illitic alluvial soils. Potassium release rates were nearly proportional to the size of the non-exchangeable pool in different soils.

Results from a large number of exhaustion experiments carried out in China reveal that rice and wheat absorbed a large proportion of the potassium from slowly available potassium in soils. Following several successively continued cultivations, 60–80% potassium absorbed by crops came from slowly available potassium (Xie and Li, 1987). After four successive crops, the amounts of potassium absorbed by rice plants from the no-K treatment varied greatly with the soil. In no-K plots, the lowest removal of potassium by rice (17 mg K kg^{-1} soil) was observed in latosols; the highest (up to 439 mg K kg^{-1} soil) removal was from fluvo-aquic soils. With an increasing number of crops, the contribution of

Table VII
Potassium Release Characteristics following Hot 1M HNO_3 Method in Samples Collected from Eight Soil Series in Rice–Wheat Growing Regions of the Indo-Gangetic Plain in India

Soil series and location[a]	Exchangeable K (mg kg^{-1})[b]	Non-exchangeable K (mg kg^{-1})[c]	K release rate (mg kg^{-1} h^{-1})[d] P_1	P_2
Nabha, Ludhiana, Punjab	67	860	356	55
Khatki, Meerut, Uttar Pradesh	72	1300	635	324
Akbarpur, Etah, Uttar Pradesh	79	1340	469	144
Rarha, Kanpur, Uttar Pradesh	72	1470	494	127
Jagdishpur Bagha, Muzaffarpur, Bihar	70	1636	543	39
Raghopur, Muzaffarpur, Bihar	70	1936	745	59
Hanrgram, Bardhaman, West Bengal	130	360	66	18
Kharbona, Birbhum, West Bengal	63	156	25	10

Source: Sekhon *et al.* (1992).

[a] Listed in order of location from trans- to lower Indo-Gangetic plains.

[b] 1M ammonium acetate extractable potassium minus water soluble K.

[c] 1M boiling HNO_3 extractable potassium minus 1M ammonium acetate extractable K.

[d] Pieri and Oliver (1987). Potassium was dissolved by 1M HNO_3 at 85°C over periods ranging from 15 min to 8 h. Potassium dissolved by the same reagent in 5 min at room temperature is taken as the extraction at zero time. P_1 is the gradient of the first linear segment and represents dissolution of external K; P_2 is the gradient of the second linear segment and represents the destruction of the lattice.

ammonium acetate extractable K was reduced, whereas increasing amounts of potassium were derived from a pool of slowly available potassium.

Studying the release kinetics of potassium under a continuous rice–wheat cropping system, Singh *et al.* (2002b) and Pannu *et al.* (2003) observed that application of organic manures (farmyard manure and green manure) along with urea-N increased the cumulative non-exchangeable potassium release and could maintain large amounts of potassium in soil solution and on exchange sites by re-establishing the equilibrium among different forms of potassium. Increased plant growth due to application of organic manures and NH_4^+-forming fertilizers applied to rice and wheat encourages acidification which in turn results in release of non-exchangeable potassium. Under NH_4^+-N nutrition, interlayer potassium can also be replaced by NH_4^+ ions that are similar to K^+ in ionic size. Acidification may also dissolve mineral potassium, a process that is irreversible (Tandon and Sekhon, 1988). According to Wihardjaka *et al.* (1999), mobilization of non-exchangeable potassium in flooded rice is due to root induced acidification, coupled with potassium removal from the soil solution by the roots.

The hydronium ion (H_3O^+) is very effective in acting as a counter-ion to replace structural potassium. Under flooded rice conditions, hydronium ions are generated by: (1) the release from roots to balance excess intakes of cation over anions under NH_4^+-N nutrition, (2) oxidation of Fe^{2+} due to released oxygen, and (3) decomposition of applied organic manures and root residues (Kirk *et al.*, 1993). The acidification increases with increase in root biomass due to better crop growth on application of fertilizers and organic manures. Thus, increased release of non-exchangeable potassium when rice and wheat are adequately fertilized is partly plant induced and partly due to solubilization of potassium caused by acidification. Experiments carried out by Rahmatullah and Mengel (2000) on release of potassium from micaceous mineral structures in five soils in Pakistan by H^+ ion resin revealed that K^+ release from the inter-layers of K^+ bearing minerals is initiated by a low K^+ concentration near the mineral surfaces. On average, quantities of K^+ released from clay and silt fractions were comparable and twice as high as from sand fractions.

Srinivasa Rao and Khera (1994) studied the potassium replenishment capacity of eight soil series in the Indo-Gangetic plain with varying illite content of their clay fraction at their minimum exchangeable K. Average daily rates of potassium replenishment of soils varied from 0.25 to 0.67 mg K kg^{-1}. Srinivasa Rao *et al.* (2000) studied fixation of potassium by soils differing in mineralogical make up and found that illitic soils fixed 23–29% of applied potassium; the values for smectitic and kaolinitic soils were 26–32% and 17–23%, respectively. The water regime is highly dynamic in rice–wheat systems and it may influence availability and fixation of potassium in soils. Flooding of dry lowland soils containing vermiculite, illite, or other 2:1 layer clay minerals may result in increased potassium fixation and reduced solution concentration, so that rice depends on non-exchangeable reserves for potassium uptake. In a long-term experiment with rice–wheat rotation in the *Tarai* plain of southern Nepal, the proportion of added potassium that was fixed in the soil ranged from 46 to 56% in a wet/dry equilibration, and fixation was linear with addition rates of up to 25 mM K kg^{-1} soil (Regmi, 1994). Since both K^+ and NH_4^+ are fixed by the same mechanism, potassium competes with ammonium for fixing sites. More potassium fixation has been reported when NH_4^+-N was applied before potassium application and less when KCl was applied alone (Singh and Singh, 1979). The work of Luo and Bao (1988) suggests that K-fixing capacity of some Chinese soils under rice–wheat systems is in the order: red soil $<$ loess $<$ yellow brown earth and the amount of potassium fixed by different soils was well correlated with clay content. Since both release and fixation of potassium in soils under flooded rice take place depending upon water regimes including continuous submergence or alternate flooding and drying, and the periodicity of such cycles (Kadrekar, 1975; Kadrekar and Kibe, 1973), measurements of non-exchangeable potassium should prove useful in studying potassium nutrition of rice–wheat cropping systems.

Soil solution potassium is kept at relatively high levels in flooded soils because large amounts of soluble Fe^{2+} and Mn^{2+} ions brought into solution displace cations from the clay complex, and exchangeable potassium is then released into the soil solution (Ponnamperuma, 1972). In fields with adequate drainage, potassium and other basic cations are lost via leaching. Leaching losses of potassium should be substantial, particularly in highly permeable wetland rice soils with low cation exchange capacity. In lower Gangetic plains in Bangladesh, Abedin *et al.* (1991) recorded leaching losses of potassium as high as 0.1–0.2 kg K ha^{-1} day^{-1}. Leaching losses of potassium will depend on soil solution concentration and percolation rates. Yadvinder-Singh *et al.* (2003b) found that leaching losses of potassium in sandy loam and loam soil profiles maintained at submerged moisture regimes were 22 and 16% of the applied K, respectively. Bijay-Singh and Sekhon (1977, 1978) studied leaching of potassium in illitic alluvial soils under different crop rotations. Estimates based on potassium saturation in subsoil layers indicated that potassium released from illitic minerals during the rainy season in the Indo-Gangetic plain can be lost via leaching beyond more than 2 m depth. In Chinese red soils under rice–wheat rotation having limited potassium absorption capabilities, leaching of potassium beyond the rooting zone constitutes a serious problem. The work of Shen (1993) carried out in field lysimeters during September 1991 to August 1992 revealed that the extent of leaching of potassium decreased in the following order of parent materials: granite > quaternary red earth > basalt > red sandstone. It was also observed that leaching of potassium decreased with cropping.

Leaching as well as potassium removal by rice and wheat in large quantities enhances release of potassium from micas by removing the reaction products and accelerates the weathering/transformation of micas to expansible 2:1 layer silicates and other weathering products. Keeping in view the existence of illite–vermiculite, illite–vermiculite–smectite or illite–smectite/chlorite–kaolinite phases, the hidden hunger for potassium and more importantly farm practices leading potassium development *vis-à-vis* weathering of potassium minerals in the trans-, upper and middle Gangetic plain to a point of no return may soon pose a great threat (Mukhopadhyay and Datta, 2001).

D. ASSESSMENT OF SOIL K-SUPPLYING CAPACITY

Using published data from several field experiments conducted during the years 1970 to 1998 across wheat growing environments in the Indo-Gangetic plains in India, Pathak *et al.* (2003) observed a relationship ($R^2 = 0.82$) between potassium uptake in no-K plots, a real measure of soil potassium supply and exchangeable soil potassium. Use of 1M ammonium acetate at pH 7.0 to extract plant available potassium (exchangeable + water soluble K) is still the most used soil potassium availability index for rice–wheat cropping systems. But its suitability as a measure of plant available potassium remains controversial, especially when soils with different textures and clay mineralogy are considered together (Kemmler, 1980; Dobermann *et al.*, 1996a,b). For example, in trans-Gangetic plains (Gurdaspur, India) 40% of soil samples were found to be deficient in potassium while only 7% of the plant samples from rice–wheat cropping systems could be called deficient in potassium (Tandon and Sekhon, 1988). The rice–wheat continuous cropping areas mostly lie in the eastern, central and northern parts of China, where the ammonium acetate extractable potassium content varies between 50 and 100 mg K kg^{-1}, whereas content of slowly available potassium (HNO_3 extractable) ranges between 300 and 800 mg K kg^{-1} (Xie *et al.*, 2000; Shen *et al.*,1998).

Soils in the Indo-Gangetic plains of India have been grouped into three categories of low, medium and high on the basis of soil test values. Usually soils analyzing < 55 mg K kg^{-1} soil by 1M ammonium acetate solution are rated as low in available potassium and soils analyzing > 110 mg K kg^{-1} soils are rated as high in available K. Depending on soil texture, clay mineralogy, and potassium input from natural resources, however, critical levels of ammonium acetate extractable potassium can vary from 39 to 156 mg K kg^{-1} soil (Yadvinder-Singh and Bijay-Singh, 2001a). In China, the yield of rice and wheat increased due to application of fertilizer potassium in soils testing < 100 mg K kg^{-1} of ammonium acetate extractable potassium. At values of available potassium $>$ 200 mg K kg^{-1}, no response to applied potassium was observed (Wu and Sun, 2002). Similar observations for wheat were recorded by Zhang (2002) in Henan province but responses were higher on loamy sandy soils compared to clay soil when available potassium was > 100 mg K kg^{-1}.

In soils with high potassium fixation and release characteristics (for example, vermicullitic soils), 1M ammonium acetate extractable potassium is often small (< 78 mg K kg^{-1}) and not a reliable soil test to assess potassium supply. Potassium saturation (% of total CEC) is often a better indicator of soil potassium supply than the absolute amount of potassium extracted with 1M ammonium acetate, because it takes into account the relationship between potassium and other exchangeable cations (Ca, Mg, Fe). The ranges for rice as suggested by Dobermann and Fairhurst (2000) are:

- K saturation $< 1.5\%$—low potassium status, response to potassium fertilizer is certain,
- K saturation 1.5–2.5%—medium potassium status, response to potassium fertilizer is probable, and
- K saturation $> 3.5\%$—high potassium status, response to potassium fertilizer is unlikely.

A measure of non-exchangeable potassium in soil is determined by boiling 1M HNO_3, but results are not always correlated to grain yields and total potassium uptake. The critical level for hot 1M HNO_3 extractable potassium (slow release K) is 98 mg K kg^{-1}. The high root density, relatively high maximum influx and low minimum solution concentrations for potassium uptake indicate that rice and wheat depend on the non-exchangeable fraction for much of their potassium supply in such soils (Meelu *et al.*, 1995). Thus, it appears desirable to include a measure of non-exchangeable potassium in our estimate of plant available potassium. Subba Rao *et al.* (1993) categorized soils on the basis of how potassium release rate was related to non-exchangeable potassium reserves in soils with different mineralogical compositions. The limits of non-exchangeable potassium for categories of very low to very high worked out by Subba Rao *et al.* (1993) were very close to those proposed by Xie *et al.* (1982, 1990) for soils in China (Table IV). Tandon and Sekhon (1988) suggested that soils with low available potassium (<100 mg kg^{-1} K soil) are expected to readily respond to potassium application. Soils with low available potassium and high reserves of potassium (>1000 mg K kg^{-1} soil) status will need lower rates of potassium application and soils with high available potassium (>100 mg K kg^{-1} soil) and low reserve potassium status can support crops for some years without potassium fertilizer application. Soils containing a (Ca + Mg):K ratio $>$ 100 may indicate low soil potassium availability to rice (Tandon and Sekhon, 1988).

There is now considerable information showing that sub-soil potassium fertility makes a significant contribution to plant nutrition, and differences in the mineralogy and reserve potassium and relationships between exchangeable potassium and water soluble potassium among soil series and soil types suggest the need for different rates of critical limits for different soils (Sekhon, 1995). In addition, ammonium acetate extractable potassium for soil testing should include soil properties such as clay content, cation exchange capacity, and organic matter content.

The EUF technique of Nemeth (1979) involving extraction of seven successive fractions of soil potassium at different voltages and temperatures over a 35-minute period has been used to study availability of potassium in soil samples collected from eight benchmark soil series in the Indo-Gangetic plain (Sekhon *et al.*, 1992). Amounts of water soluble potassium in soils should have been comparable to that of those desorbed using EUF during the first 10 minutes (EUF_{10}) (Table VIII). However, in illite dominant alluvial soils where the rice–wheat system is practised in the Indo-Gangetic plains, water soluble potassium was generally more than EUF_{10}; the reverse was true in smectite and kaolinite dominant soils from Hanrgram and Kharbona in lower Gangetic plains. These trends were due to the higher affinity of illitic minerals for potassium as compared to those of smectite and kaolinite. The EUF-K quotient ($\mathrm{EUF}_{30-35}/\mathrm{EUF}_{30}$) estimates the preponderance of difficult-to-extract potassium and is therefore considered a measure of buffering power. This quotient is generally higher in illite and smectite dominant soils than in kaolinite dominant ones (Brar and Sekhon, 1986; Subba Rao *et al.*, 1988). Buffering capacity of soils in the Indo-Gangetic plains to maintain concentration of potassium in soil solution at a satisfactory level has also been studied using the concept of quantity–intensity relations. Soils containing predominantly illitic or smectitic clays possessed higher buffering capacity and

Table VIII

Availability Indices of Soil Potassium as Estimated by Different Extractants and Following Electroultrafiltration (EUF) Technique in Samples Collected from Six Soil Series in Rice–Wheat Growing Regions of the Indo-Gangetic Plain in India

Soil series[a]	Water soluble K (mg K kg^{-1})	1M ammonium acetate extractable K (mg K kg^{-1})	1M HNO_3 extractable K (mg K kg^{-1})	EUF_{10}[b] (mg K kg^{-1})	EUF_{30} (mg K kg^{-1})	EUF_{30-35} (mg K kg^{-1})	EUF_{35} (mg K kg^{-1})	$EUF - K_Q$[c]
Nabha	35.7	119	990	29.2	60.9	25.4	86.3	0.45
Khatki	15.4	91	1278	13.4	34.4	23.6	58.0	0.68
Akbarpur	26.3	134	1440	25.2	61.0	39.4	100.4	0.71
Rarha	15.3	88	1480	14.0	35.2	27.8	63.0	0.83
Hanrgram	9.1	131	446	23.9	61.0	21.6	82.6	0.37
Kharbona	15.6	45	125	18.1	27.6	4.9	32.5	0.21

Source: Sekhon *et al*. (1992).

[a] Listed in order of location from trans- to lower Indo-Gangetic plains.

[b] Subscripts of EUF indicate time for which the soil sample was subjected to electroultrafiltration.

[c] $EUF - K_Q = EUF_{30-35}/EUF_{30}$.

lower potassium activity ratios than the corresponding kaolinite-dominant soils. Also, fine textured soils exhibited higher potassium buffering capacity than those with coarse textures (Sekhon *et al.*, 1992). A significant positive relationship was observed between clay content and buffer capacity in illitic alluvial soils; potassium activity ratios were negatively correlated with clay content of soils (Subba Rao and Sekhon, 1989). Although quantity–intensity relationships involve probably only planar and edge K, these indicate that for a given level of soil solution K, the quantity varies widely for soils with different mineralogy. Thus to obtain a given amount of potassium in soil solution, more than double the amount of adsorbed potassium is needed in smectitic soils than in illitic or kaolinitic soils. The critical levels of available potassium would, therefore, be different for soils of widely different mineralogical composition.

The standard approach to soil fertility management revolves around identification of K-deficient soils or plant potassium deficiency using rapid chemical tests with empirical critical threshold ranges. This approach relies on a large number of field experiments to establish calibrations between a given soil potassium test value and the profitability of a response to applied potassium. On soils with relatively high native fertility and little potassium fixation character, this approach may be adequate to provide reasonable recommendations for potassium input requirements. However, such an approach is greatly inadequate for intensively irrigated rice–wheat systems in Asia. This is because these systems are very highly K-demanding. Extractable potassium levels can fluctuate enormously and many soils under rice–wheat systems also have strong K-fixation properties. Dobermann *et al.* (1996b) evaluated several chemical tests for assessing the K-supplying power of rice soils. They observed a positive correlation between potassium uptake and extractable K, potassium saturation of CEC and CEC of the clay fraction. Despite the significant correlations, none of these static measures provided a reliable estimate of potassium uptake across the different soils. These chemical tests of potassium availability were not suitable indicators of potassium status in soils with K-fixing clay minerals. Extractable potassium alone explained only 53% of total potassium uptake in the NP and NPK treatments. Several regression models were evaluated to improve the prediction of total potassium uptake by incorporating other static soil tests that seemed to provide additional factors affecting soil potassium supply in rice soils. A regression model combining commonly used static soil test parameters that appeared to integrate measures of potassium release from non-exchangeable forms as well as chemical factors affecting potassium activity in soil solution explained 72% of the crop potassium uptake by rice. The integrative term accounts for (1) potential potassium release from non-exchangeable fractions, and (2) potassium exchange equilibrium and potassium activity as affected by Ca and Mg. However, this approach would require determination of six soil properties and it does not provide a direct measure of potassium release dynamics.

All chemical soil tests used for potassium for rice and wheat production have theoretical limitations, including that (1) nutrient availability in irrigated rice–wheat ecosystems is extremely dynamic and tests on air-dried soil may not fully reflect nutrient status after submergence, (2) differences in clay mineralogy and physical properties have a strong impact on desorption characteristics and plant availability, (3) unextracted nutrient pools may also contribute to plant uptake, (4) diffusion is a key process of potassium transport to the root surface, (5) external mechanisms such as root-induced solubilization of P by acidification contribute significantly to uptake by rice and wheat roots, and (6) kinetics of nutrient release are not measured. Traditional methods are based on extractants' snapshots of the amounts of nutrients in specific nutrient pools. These give little information on the dynamics of inter-pool conversions and the potential rate of nutrient supply to a growing root surface. Therefore, ion exchange resins have attracted considerable attention as an alternative method for estimating bioavailable potassium in a more dynamic manner. Resins maintain low ion concentrations in solution, thereby stimulating further release from soil solids. Compared with static extraction soil tests, resin incubation techniques assess the nutrient supply to a strong resin sink over a longer time period and, in most cases, they can account for diffusion as one process controlling the amount of potassium adsorbed on the resin. Dobermann *et al.* (1996b) assessed the soil potassium-supplying capacity using mixed-bed ion exchange resin capsules. The resin method was sensitive to past fertilizer history and the resulting build-up and depletion of soil potassium reserves and it was a better predictor of total potassium uptake (K uptake; kg $\mathrm{ha}^{-1} = -11 + 83a_\mathrm{K} + 227b_\mathrm{K}$; $r^2 = 0.82$, where $a_\mathrm{K} =$ initial resin K adsorption rate; $b_\mathrm{K} =$ resin K adsorption rate coefficient) than static soil tests. The coefficient a_K expresses the rapid potassium adsorption by the resin capsule. The coefficient b_K characterizes the capability of a soil to maintain a nutrient flux to a strong sink such as a resin or a plant root. The resin capsule method also known as a phytoavailability soil test has the potential to become a valuable method for assessing soil nutrient-supplying capacity, not only for K, but practically all essential plant nutrients across a wide range of soil types.

V. POTASSIUM UPTAKE BY RICE–WHEAT CROPPING SYSTEMS

Field crops generally absorb potassium faster than they absorb nitrogen or phosphorus or build up dry matter. The removal of potassium depends on the production level, soil type and whether crop residues are removed or recycled in the soil. When crop residues are retained in the field, large amounts of potassium are recycled. Optimum application of nitrogen increased potassium uptake by 57% over control plots and nitrogen and phosphorus application increased potassium uptake by 145% (Tandon and Sekhon, 1988). The amount

Table IX
Potassium Removal by Rice–Wheat Cropping Systems in the Indo-Gangetic Plains and in China

Cropping system	Total productivity ($t\ ha^{-1}$)	K uptake ($kg\ ha^{-1}$)	Reference
Rice–wheat	13.2	287	Kanwar and Mudahar (1986)
Rice–wheat–cowpea	9.6 + 3.9 (dry)	324	Nambiar and Ghosh (1984)
Rice–wheat–jute	6.9 + 2.3 (fibre)	212	
Rice–wheat	8.8	280	Sharma and Prasad (1980)
Rice–wheat–mungbean	11.2	279	Meelu *et al.* (1979)
Rice–wheat	10.7	238	Bhandari *et al.* (2002)
Rice–wheat	9.9	152	Bao and Xu (1993)
Rice–wheat	10.7	142	
Rice–rice–wheat	8.1	150	Regmi *et al.* (2002b)
Aman rice–wheat	5.7	132	Saunders (1990)
Aman rice–wheat– Aus rice	8.1	185	

of potassium removed by rice–wheat cropping systems from the soil can be as high as 325 kg K ha^{-1} in the Indo-Gangetic plains (Table IX). In China, Nepal and Bangladesh, uptake of potassium by rice–wheat cropping systems has been reported around 150 kg K ha^{-1}, generally due to low wheat yields. Table X lists the typical ranges and averages for potassium uptake and content in grain and straw of modern rice and wheat varieties. Grains of wheat contain more potassium than rice; the opposite is true for straw. It has been shown that nutrient requirement per unit of grain of rice is nearly the same for all dwarf varieties although variations between varieties of a crop and variations of the same variety between two different seasons have also been observed.

The pattern of K uptake follows most closely that of vegetative growth. Even before the booting stage, 75% of the maximum K content has been taken up, and most of the remaining uptake is completed before grain formation begins, very

Table X
Uptake and Content of Potassium in Modern Rice and Wheat Varieties

	Typical range		Observed average	
Plant part	Rice	Wheat	Rice	Wheat
Potassium uptake (*kg* t^{-1}*of grain or straw*)				
Grain	2–3	4–5	2.5	4.5
Straw	12–17	9–12	14.5	10.5
Potassium concentration (%)				
Grain	0.22–0.31	0.35–0.50	0.27	0.43
Straw	1.17–1.68	0.85–1.15	1.39	1.00

Source: Yadvinder-Singh and Bijay-Singh (2001a); Dobermann and Fairhurst (2000).

similar to the pattern of K uptake in wheat. About 20% of the K taken up before full heading is translocated to the panicles and the rest remains in the vegetative parts at maturity (De Datta and Mikkelsen, 1985). Out of the total potassium uptake by rice, about 55% of potassium is absorbed during the early panicle initiation stage. About 60% of potassium uptake is completed by the heading stage (Pillai and Kundu, 1993). In China, 78% and 76% of potassium uptake was completed by the jointing stage in rice and the booting stage in wheat, respectively (Lu, 1998).

VI. RESPONSE OF RICE–WHEAT CROPPING SYSTEMS TO APPLIED POTASSIUM

Yield response to applied potassium is a function of crop, variety, soil characteristics, attack of pests and diseases, and application of other nutrients. Rice tends to respond more to potassium than wheat. Possibly, due to retarded respiration rates of roots under anaerobic soil conditions, adequate absorption of potassium by rice roots can only be ensured by high potassium levels in the soil. Studies carried out on a large number of on-farm locations showed that application of 50 kg K ha^{-1} produced a grain yield response of 290 and 240 kg ha^{-1} in wheat and rice, respectively (Randhawa and Tandon, 1982). Average agronomic response of 6 kg grain kg^{-1} K to an application of 37.5 kg K ha^{-1} was observed in rice and wheat. In later studies carried out in Punjab, Haryana and Uttar Pradesh in the trans-Indo-Gangetic plains, response of rice to 25–50 kg K ha^{-1} ranged from 210–370 kg grains ha^{-1} (Meelu *et al*., 1992). In the western part of the Indo-Gangetic plains located in Pakistan, Zia *et al*. (2000) observed 11 and 19% increases in grain yields of rice and wheat, respectively, due to application of 62 kg K ha^{-1} as potassium chloride in a 7-year experiment on a rice–wheat cropping system. In on-farm experiments carried out at several locations in Punjab in Pakistan, average response of rice and wheat to application of 50 kg K ha^{-1} was only 1.3 and 0.12 t ha^{-1} (NFDC, 2001). Dobermann *et al*. (1995) observed significant yield increase of 12% to potassium application in rice at Pantnagar. In a 5-year field study on a sandy loam soil (ammonium acetate extractable potassium; 123 kg ha^{-1}), application of 25 kg ha^{-1} resulted in a mean increase in yield of rice and wheat by 280 and 160 kg grain ha^{-1}, respectively, (Meelu *et al*., 1995). In a number of long-term experiments on rice–wheat systems located all over the Indo-Gangetic plain (Table XI), average response to application of 33 kg K ha^{-1} over 120 kg N and 35 kg P ha^{-1} to each crop ranged from 0 to 0.5 t ha^{-1} in rice and 0 to 1.3 t ha^{-1} in wheat. The low responses to fertilizer potassium observed in rice and wheat on alluvial soils of the Indo-Gangetic plain suggest that release of native potassium from illitic minerals in these soils could meet the potassium needs of these crops.

Table XI
Response of Sequentially Grown Rice and Wheat to Application of Potassium in Long-term Experiments in the Indo-Gangetic Plains of India

			Grain yield (t ha^{-1})			
Location	Years	Crop	No NPK	N	NP	NPK
Barrackpore[a]	1972–97	Rice	1.6	3.5	3.9	4.0
		Wheat	0.8	2.1	2.3	2.4
Pantnagar[a]	1972–96	Rice	3.4	5.0	5.0	5.4
		Wheat	1.6	3.8	3.8	3.9
R.S. Pura	1981–90	Rice	2.1	4.2	4.8	4.8
		Wheat	1.1	1.9	3.1	3.5
Palampur	1978–89	Rice	2.3	4.1	4.0	4.5
		Wheat	1.2	1.3	2.4	3.7
Faizabad	1977–90	Rice	1.0	3.9	4.7	4.8
		Wheat	0.8	3.6	4.5	5.5
Kanpur	1977–87	Rice	1.7	3.5	4.2	4.4
		Wheat	1.2	3.5	4.1	4.2
Pantnagar	1977–90	Rice	2.3	4.0	4.2	4.4
		Wheat	1.4	3.5	3.5	3.5
Varanasi	1977–88	Rice	2.1	4.1	3.7	3.8
		Wheat	1.3	3.1	3.5	3.6
Rewa	1978–90	Rice	2.0	3.9	4.1	4.2
		Wheat	1.0	1.5	2.7	2.9

Source: Hegde and Sarkar (1992).
[a] Swarup (1998).

Using time series analyses, Bhargava *et al.* (1985) showed that response to potassium has been increasing with time. The response of wheat to potassium in different agro-ecological regions was in the range of 6.7–12.7 kg grain kg^{-1} K during 1977–1982 as against 2.0–5.0 kg grain kg^{-1} K during 1969–1971. The corresponding values for rice were 6.5–10.7 kg and 1.8–8.0 kg grain kg^{-1} K (Table XII). The increasing trend in response to potassium over the years suggests the need for its application in intensive rice–wheat cropping systems.

A large proportion of area (about 2.8 Mha) in the Indo-Gangetic plain is highly alkaline ($pH > 8.5$) and contains an excessive concentration of soluble salts, a high exchangeable sodium percentage ($>15\%$) and $CaCO_3$. Swarup and Singh (1989) found that application of fertilizer potassium did not significantly increase crop yields in rice–wheat rotation on reclaimed sodic soils in Haryana even after continuous cropping for 12 years. However, in salt affected soils of Kanpur, application of 25 kg K ha^{-1} to both crops produced additional grain yield of 0.50 and 0.61 t ha^{-1} of rice and wheat, respectively (Tiwari *et al.*, 1998).

Table XII
Response of Rice and Wheat over Different Periods to Applied Potassium in Different Agro-ecological Regions in India

	Response of 50 kg K ha^{-1} (kg grain kg^{-1}K)			
	Rice		Wheat	
Region	1969–71	1977–1982	1969–71	1977–82
Humid, western Himalayan	8.0	10.7	5.0	12.7
Subhumid, Satluj-Ganga Alluvial Plain	4.8	7.0	3.4	7.8
Subhumid to humid Eastern Uplands	4.4	9.8	2.0	7.1
Arid western Plains	1.8	6.5	2.6	6.7

Source: Bhargava *et al*. (1985).

In a 20-year long-term experiment with rice–rice–wheat rotation in the Tarai region of Nepal, the average yield of wheat increased from 1.2 t ha^{-1} in NP treatment to 2.3 t ha^{-1} in NPK (100 kg N + 18 kg P + 25 kg K ha^{-1}) (Regmi *et al*., 2002b). Response of first and second crops of rice to application of 25 kg K ha^{-1} on the top of 100 kg N and 13 kg P ha^{-1} was only 0.2 and 0.6 t ha^{-1}. Similar increases in grain yield of rice and wheat during 1995–1999 when potassium was applied to a plot receiving only N and P fertilizers during 1988–1994 were also observed (Regmi 2002a).

A wide range of responses of rice–wheat cropping systems to application of potassium were also observed in China. Application of 90 kg K ha^{-1} to rice as well as wheat resulted in a 12–29% increase of total grain yield in Jiangsu province. The increase was 29–55% with application of only 37.5–56 kg K ha^{-1} to rice as well as wheat in Sichuan province (Table XIII). Similar increases in total productivity of a rice–wheat cropping system were observed when only potassium was applied to rice (180 kg K ha^{-1}) in Jiangsu province and to wheat (75 to 112 kg K ha^{-1}) in Sichuan province (Table XIII). However, within Jiangsu province, application of potassium exhibited a higher direct effect on wheat and residual effect on rice in Entisols rather than in Alfisols (Table XIV). In a long-term experiment in Hubei province, Chen (1997) observed that the direct response of wheat to potassium application was larger than that of rice, while the residual response of rice was larger than that of wheat. In a large number of balanced fertilization demonstration trials carried out during more than a decade in southern China, application of 48–75 kg K ha^{-1} to rice resulted in grain yield responses of 7.9–61.3% and application of 46–62 kg K ha^{-1} to wheat increased the grain yield by 6.9–23.2% (Scientific Technology Department of Ministry of Agriculture, 1991). In general, potassium application shows larger yield responses on wheat than on rice. Thus when potassium fertilizer is not available in sufficient quantity, it is preferably applied to wheat (Xie *et al*., 2000).

Table XIII

Response of Rice–Wheat systems to Application of Potassium in Different Modes in Northern Jiangsu Province and Sichuan Province of China

Location and K level (kg K ha^{-1})	Mode of K application	Yield of rice (t ha^{-1})	Yield of wheat (t ha^{-1})	Yield of rice + wheat (t ha^{-1})[a]	Per cent increase over no-K plot
Siyang (Jiangsu)[b]	0	8.2	6.0	14.2d	
1.0 = 180 kg K ha^{-1}	0.5 to rice, 0.5 to wheat	9.1	6.8	15.9b	12.0
	1.0 to wheat	8.4	6.9	15.3c	7.7
	1.0 to rice	9.5	6.7	16.2a	14.1
Liyang (Jiangsu)[c]	0	7.6	1.6	9.2c	
1.0 = 180 kg K ha^{-1}	0.5 to rice, 0.5 to wheat	9.0	2.9	11.9a	29.3
	1.0 to wheat	8.0	3.0	11.0b	19.6
	1.0 to rice	9.3	2.5	11.8a	28.3
Emei (Sichuan)[d]	0	5.3	0.9	6.2	
1.0 = 75 kg K ha^{-1}	0.5 to rice, 0.5 to wheat	5.8	2.2	8.0	29.0
	1.0 to wheat	5.7	2.9	8.6	38.7
	1.0 to rice	1.1	6.0	7.1	14.5
Leshan (Sichuan)[e]	0	5.1	0.4	5.5	
1.0 = 75 kg K ha^{-1}	0.5 to rice, 0.5 to wheat	6.5	1.7	8.2	49.1
	1.0 to wheat	6.4	2.6	9.0	63.6
	1.0 to rice	0.6	6.8	7.4	34.5
Qingshen (Sichuan)[f]	0	5.1	0.7	5.8	
1.0 = 112 kg K ha^{-1}	0.5 to rice, 0.5 to wheat	5.8	3.2	9.0	55.2
	1.0 to wheat	5.5	3.7	9.2	58.6
	1.0 to rice	1.1	5.9	7.0	20.7

Source: Chen and Zhou (1999); Nong *et al.* (1993).

[a] Values in a column for a particular site followed by same letter are not significantly different at $p = 0.05$.

[b] pH 8.1, ammonium acetate-K 47.3 mg kg^{-1}, HNO_3-K 546.4 mg kg^{-1}.

[c] pH 8.3, ammonium acetate-K 65.6 mg kg^{-1}, HNO_3-K 153.6 mg kg^{-1}.

[d] Alluvial yellow earth, ammonium acetate-K 46 mg kg^{-1}.

[e] Acid purple soil, ammonium acetate-K 11 mg kg^{-1}.

[f] Old alluvial yellow earth, ammonium acetate-K 52 mg kg^{-1}.

Interestingly, the F1 hybrid rice cultivars take up more K due to a well-developed root system and vigorous growth than do the ordinary rice varieties (Xu and Bao, 1995). For example, at the same yield of 7.5 t ha^{-1} of rice grains, the K uptake by hybrid rice was 218 kg ha^{-1} compared to only 156–187 kg ha^{-1} by ordinary rice cultivars. The yield potential of hybrid rice is greater than that of ordinary varieties, when soil fertility is high or large amounts of fertilizers are used, but hybrid varieties often yield less than most of the ordinary varieties when grown on K-deficient soils. The beneficial effect of K is more likely with hybrid rice than with ordinary varieties (Fan and Tao, 1981).

Table XIV
Direct and Residual Effects of Application of Different Levels of Potassium to Sequentially Grown Rice and Wheat in Alfisols and Entisols of Jiangsu Province of China

Experiment 1			Experiment 2		
K levels applied to rice (kg ha^{-1})	Direct effect rice yield (t ha^{-1})	Residual effect wheat yield (t ha^{-1})	K levels applied to wheat (kg ha^{-1})	Direct effect wheat yield (t ha^{-1})	Residual effect rice yield (t ha^{-1})
Alfisol[a]					
0	7.3	3.7	0	3.9	6.8
83	7.8	4.0	83	4.5	7.8
166	8.1	4.2	166	4.6	8.0
Entisol[b]					
0	7.4	4.0	0	3.6	6.2
83	7.7	4.4	83	4.3	6.7
166	7.9	4.6	166	4.7	7.1

Source: Zhu *et al*. (2000).
[a] pH 6.3, ammonium acetate-K 116 mg kg^{-1}, HNO_3-K 725 mg kg^{-1}, clay 28.2%.
[b] pH 8.0, ammonium acetate-K 67 mg kg^{-1}, HNO_3-K 625 mg kg^{-1}, clay 21.2%.

A. Time, Source and Method of Potassium Application

The common recommendation is to apply a full dose of potassium as basal at puddling for rice and at sowing for wheat. When cation exchange capacity of the soil is low and drainage in soil is excessive, basal application of potassium to rice should be avoided. As rice and wheat require large quantities of potassium, a sustained supply is necessary up to heading stage when the reproduction stage is complete. On coarse textured soils, split application of fertilizer potassium in both rice and wheat may give higher nutrient use efficiency than its single application due to reduction in leaching losses and luxury consumption of potassium (Tandon and Sekhon, 1988). Tiwari *et al.* (1992) have cited several references showing a distinct benefit of applying potassium in split doses. In trans-Indo-Gangetic plains, Kolar and Grewal (1989) reported a yield advantage of 250 kg grains ha^{-1} by split application of potassium (half at transplanting + half at active tillering stage) as compared with single application at transplanting. Similarly, in a sandy loam soil of Uttar Pradesh, Singh and Singh (1987) reported a yield advantage of 440–490 kg grain ha^{-1} in wheat by split application of potassium as compared to a single application. At sowing of wheat and transplanting of rice, potassium fertilizers are normally applied by drilling, placement or broadcast followed by incorporation.

In China, a number of experiments carried out in provinces where a rice–wheat cropping system is followed have shown that application of potassium to each of the two crops can be more beneficial than applying the total quantity to one of the crop (Scientific Technology Department of Ministry of Agriculture, 1991). However, in some regions where one of the two crops shows very high response to potassium application than the other, application of whole of potassium to one crop can prove more beneficial (Table XIII). Application of potassium fertilizers as basal manure or combining basal manuring with early top dressing has shown better results in both rice and wheat. In sandy soils, top dressing of potassium has been preferred. Shallow tillage has been recommended when potassium fertilizer is applied before planting of rice or wheat. Top dressing of potassium fertilizer to rice is done when there is no standing water in the field (Xie *et al*., 2000; Shen *et al*., 1998; Xie and Zhou, 1999).

Murate of potash (KCl) is a major fertilizer potassium source for rice and wheat because of its low cost and high potassium analysis. However, its use in salinity affected areas is discouraged. Potassium sulphate may be used in areas with S deficiency (Zia *et al*., 2000). In the Indo-Gangetic plains, 99% of the total fertilizer potassium applied is KCl and no overall significant difference was observed between KCl and potassium sulphate (Tandon and Sekhon, 1988).

Foliar application involves the use of K fertilizer in solution. It results in fast K absorption and utilization and has the advantage of quickly correcting deficiencies diagnosed by observation or foliar analysis. Other advantages are low application rates, and uniform distribution of fertilizer. However, foliar fertilization is supplementary to and cannot replace the basal fertilization (Kafkafi *et al*., 2001). In rice, a foliar application of 10 kg KCl m^{-3} at panicle initiation, boot leaf and 50% flowering stages, both in the monsoon and winter seasons, significantly increased seed yield and improved quality (seed germination and 100-seed weight) (Jayaraj and Chandrasekharan, 1997). Splitting a total of 95 kg ha^{-1} of KCl to rice, a third at sowing in soil, a third as a foliar spray at flag leaf stage and a third as foliar spray at grain development, gave larger yields than a soil application all at sowing (Narang *et al.,* 1997). In China, a foliar spray applying 3.9 kg K ha^{-1} (as 10 kg KCl m^{-3}) three times at one-week intervals from full head of rice cv. Wuyuegen increased grain yield from 7850 kg ha^{-1} in the control plots, sprayed only with water, to 8500 kg ha^{-1} (Kadrekar, 1975). It is unclear whether K or Cl contributed to the increased grain yield. Foliar spray of 10 kg KCl m^{-3} and 10 kg urea m^{-3} from the jointing stage and the full heading stage increased the N and K content in the plants and stimulated N translocation to the grain, increasing the protein content of wheat grain by 15 g kg^{-1}. However, only the grain yield of wheat was significantly increased by the foliar spray (Xu *et al*., 1999).

B. INTERACTIONS OF POTASSIUM WITH OTHER NUTRIENTS

The interaction among plant nutrients is a common feature of crop production. Potassium plays an important role in ensuring efficient utilization of nitrogen. Large quantities of nitrogen used in intensive rice–wheat cropping systems encourage crop uptake of nitrogen and potassium and in turn heavy depletion of soil potassium. Application of nitrogen and phosphorus resulted in 145% increase in potassium uptake as compared to a control (Tandon and Sekhon, 1988). If insufficient nitrogen and phosphorus or other essential plant nutrients restrict the crop development, the amount of potassium present even at low soil test values may be sufficient to meet crop needs. Tiwari *et al*. (1992) reported that response to potassium application in rice as well as wheat increased with increasing rate of nitrogen application. In order to obtain high yields of rice and wheat, application of an increasing rate of potassium with increasing levels of nitrogen was suggested. A positive N×K interaction observed for rice in the lower Indo-Gangetic plains revealed that at higher rates of fertilizer nitrogen, higher levels of potassium application were needed to achieve high yields and that the N×K interaction was more important in the dry season rather than the wet season (Mondal, 1982). A marked interaction between nitrogen and potassium applied to rice has been observed even in the following crop of wheat to which no potassium was applied (Table XV).

As potassium, calcium and magnesium perform both specific and non-specific functions in plants, in the event of better supplies of one, the uptake of other nutrients may be reduced. In the Indian Punjab, Stillwell *et al*. (1975) observed luxury consumption of potassium by wheat beyond an application of 26 kg K ha^{-1} and this was accompanied by a reduction in the uptake of Ca + Mg.

Table XV
Residual Effect of Applying Different Levels of Nitrogen and Potassium to Rice on the Following Crop of Wheat in Entisol and Alfisol Soils in Jiangsu Province in China

	Wheat[a] grain yield in Alfisol (t ha^{-1})			Wheat[a] grain yield in Entisol (t ha^{-1})		
	N levels (kg N ha^{-1})			N levels (kg N ha^{-1})		
K level (kg K ha^{-1})	200	250	300	200	250	300
0	3.61	3.41	3.46	4.49	4.73	4.68
83	3.65	3.68	3.74	4.77	5.04	5.05
166	3.78	3.89	3.93	4.81	5.12	5.57

Source: Zhu *et al*. (2000).

[a] A uniform dose of 250 kg N ha^{-1} and no potassium was applied to wheat.

C. EFFECT OF POTASSIUM FERTILITY STATUS OF SOILS ON RESPONSE TO POTASSIUM

On-farm studies suggest large variability in soil nutrient supply and response of rice and wheat to applied nutrients. The uniform adoption of blanket fertilizer recommendations, therefore, does not ensure economy and efficiency of potassium use since the variation in soil fertility is not taken into account. There will be wastage of fertilizers in some cases while under-usage in others. Responses of rice and wheat to potassium application are expected to be high on soils testing low in 1M ammonium acetate extractable potassium than on high potassium soils (Tandon and Sekhon, 1988). Significant responses of wheat to applied potassium were observed up to 25 kg K ha^{-1} on soils testing low in available potassium in Punjab, but no significant increase in wheat yield was observed on soils testing medium and high in available potassium (Sharma *et al.*, 1978; Stillwell *et al.*, 1975; Yadvinder-Singh and Khera, 1998). Rana *et al.* (1985) observed that rice responded to 50 kg K ha^{-1} on soils testing low and medium in available potassium, but no significant response to applied potassium was observed on soils testing high in available potassium. Experiments carried out by Kapur *et al.* (1984) revealed that wheat responded up to a dose of 75 kg K ha^{-1} on low potassium soils and up to 50 kg K ha^{-1} on medium and high potassium soils. On the same lines, Azad *et al.* (1993) observed that wheat yield increased significantly up to 75 kg K ha^{-1} on soils testing low in available potassium, whereas significant increase in wheat yield was observed only at 25 kg K ha^{-1} on soils testing medium as well as high in available K. Based on results of more than 2200 trials with wheat, a similar relationship was observed by Tandon (1980). Tandon and Sekhon (1988) concluded that the response of high yielding varieties of rice and wheat to potassium application in soils rated medium in available potassium were only marginally lower than responses in low potassium soils. Such results emphasize the need for a fresh look at soil fertility limits used for categorizing soils into low, medium and high with respect to available K, particularly for highly productive rice–wheat cropping systems.

A large proportion of the total removal of potassium by 2 or 3 cycles of wheat–rice rotations at two locations in Taihu region of south Jiangsu province in China was found to come from non-exchangeable or interlayer pools of potassium in the soil (Bao and Xu, 1993). When fertilizer potassium was applied, contribution of non-exchangeable potassium to total potassium removal was reduced. Experiments carried out in the Indo-Gangetic plains (Tiwari *et al.*, 1992) also suggest that contribution of non-exchangeable potassium fractions to the nutrition of rice and wheat was 89% when no potassium was applied and 56% when fertilizer potassium was applied at 50 kg K ha^{-1} to both rice and wheat. In a long-term experiment on a rice–wheat system initiated in 1977–78 at Faizabad in the middle Indo-Gangetic plains, both the crops did not respond to applied potassium in the first 10 years. Thereafter, responses to applied potassium started increasing; higher response was observed in wheat (Yadav *et al.*, 2002). The release of potassium from a non-exchangeable pool was responsible for the lack of response during the initial years. Response of rice to application of potassium in Chinese soils was found to be strongly influenced by the HNO_3 extractable potassium content in the soils (Table XVI). Response of rice to applied potassium also increased substantially when soil potassium was exhausted by continuous cropping (Xie and Li, 1987). Field experiments conducted at different locations in the Indian Punjab showed that rice responded more to applied potassium in northeastern districts (Gurdaspur, Amritsar, Kapurthala, and Hoshiarpur) than in central and southwestern districts (Ludhiana, Bathinda, Sangrur, and Ferozepur) (Singh and Bhandari, 1995). The values of available potassium in soil ranged from 150–180 kg K ha^{-1} in northwestern districts to 112–165 kg K ha^{-1} in central and southwestern districts. A recent 6-year study conducted at two locations in northwestern India showed that both rice and wheat responded significantly to potassium application up to 50 kg K ha^{-1} on loam soil at Gurdaspur, whereas no significant increase in rice yields was observed on sandy loam soil at Ludhiana (Yadvinder-Singh *et al.*, 2002a). Wheat started responding to potassium application at Ludhiana two years after the initiation of the experiment. Although soils at both the locations tested low in ammonium acetate extractable potassium, higher response at Gurdaspur was due to high K-fixation capacity and slow K-release rate of the loam soil.

Table XVI

Response of Three Continuous Crops of Rice to Applied Potassium in Soils Containing Different Amounts of Slowly Available Potassium (HNO_3 Extractable Potassium)

Slowly available K (mg K kg^{-1})	Number of soil samples	Increase in dry matter yield of rice due to potassium application (% over no-K control)		
		1st crop	2nd crop	3rd crop
<66	6	237	–[a]	–
66 ~ 166	4	117	1870	–
166 ~ 330	6	53.6	392	–
330 ~ 500	5	15.8	98.0	631
500 ~ 750	5	4.3	72.8	504
750 ~ 1160	6	2.8	57.2	187
>1160	3	−0.1	10.6	39.6

Source: Xie and Li (1987).

[a] Plants died in the control treatment.

These results suggest that potassium supplying capacity of different soils is governed by pools of potassium other than water soluble plus exchangeable potassium.

Key components of potassium management should include: (1) an estimate of crop potassium demand, potential indigenous potassium supply, and recovery of potassium from applied inorganic and organic sources to predict the potassium inputs required to maintain a targeted yield level, (2) a schedule for timing potassium applications depending on soil potassium buffering characteristics and an understanding of the relationship between potassium nutrition and pest incidence and (3) knowledge of the relationship between the potassium budget, residual effects of potassium fertilizers, and changes in soil supply over time. Among the new approaches, the target yield approach has found popularity in India (Srivastava and Subba Rao, 2000). This method not only estimates soil test based fertilizer dose but also the level of yield the farmer can achieve with a particular dose. Velayutham *et al.* (1985) described the use of the targeted yield approach for making fertilizer recommendations to different crops. This approach as based on soil tests has three basic steps: (1) the potassium requirements for specific yield targets are worked out from the nutrients removed by the above ground harvested biomass; (2) using soil test values the proportion of nutrient extracted by the suitable extractant that actually becomes available to crops during the growth period is estimated; and (3) the fertilizer recommendations are based on the apparent recovery of applied nutrient under a standard set of agronomic practices. Fertilizer doses are worked out by subtracting the amount that is likely to be made available by the soil to crop at a known soil test value. Based on the above basic data, fertilizer doses are worked out for a target yield relationship. In this approach, it is assumed that there is a linear relationship between grain yield and nutrient uptake by a crop. Quantitative fertilizer requirements based on this approach have been estimated for specific yield targets of rice and wheat (Velayutham *et al.*, 1985; Ahmed *et al.*, 1999; Srivastava and Subba Rao, 2000). Sharma *et al.* (2000) evaluated the targeted yield approach for fertilizer recommendations in wheat *vis-à-vis* general fertilizer recommendations at three locations in Delhi state. The results revealed that the moderate yield target of 5 t ha^{-1} could be achieved with a deviation of $\pm 10\%$ along with higher response ratio and net profit as compared to general recommended dose and farmers' practice.

D. SITE-SPECIFIC POTASSIUM MANAGEMENT FOR RICE AND WHEAT

Site-specific nutrient management focuses on developing a nutrient management program taking into account: (1) regional and seasonal differences in the climatic yield potential and crop nutrient demand, (2) between field spatial variability in indigenous nutrient supply, (3) field-specific within-season dynamics of crop nutrient demand, and (4) location-specific cropping systems and crop management practices. The basic data required for formulating fertilizer recommendation using this approach are: (1) climatic yield potential, (2) yield goal, (3) definition of the relationship between grain yield and plant nutrient accumulation, (4) field-specific estimates of the indigenous nutrient supplies, and (5) estimated recovery efficiencies of fertilizer. The distinct characteristic of the site-specific nutrient management approach developed for rice and wheat is the use of crop-based estimates of the indigenous nutrient supply instead of relying on soil tests. The modification of the QUEFTS (Quantitative Evaluation of Fertility of Tropical Soils) model developed by Janssen *et al.* (1990) has been used to work out field-specific recommendations for nitrogen, phosphorus and potassium for each site at the beginning of each season.

It has been established that crop yields, profit, plant nutrient uptake, and nutrient use efficiencies can be significantly increased by applying fertilizers on a field-specific and cropping season specific basis (Dobermann and White, 1999). On-farm experiments conducted at 179 locations over a period of four cropping seasons during 1997–1999 in Asia have shown that the improved techniques of site-specific nutrient management can contribute to productivity increases of 6–8% (0.31–0.41 t ha^{-1}) in rice. Yield and income gains were much higher in well managed farms (Dobermann *et al.*, 2002). Fertilizer potassium rates predicted by the QUEFTS model to achieve the target yields and maintain the soil indigenous potassium supply were, on average, higher than the amounts currently applied by the farmers. Potassium rates in site-specific nutrient management plots ranged from 50 to 66 kg K ha^{-1} per crop, while the average farmer fertilizer potassium rate was 30 kg K ha^{-1}.

Wang *et al.* (2001) evaluated the site-specific nutrient management approach for irrigated rice in southern China on 21 sites. The indigenous potassium supply ranged from 70 to 180 kg K ha^{-1}. The extractable potassium ranged from 47 to 330 mg K kg^{-1}. Compared with farmers' practice, site-specific nutrient management significantly increased grain yields and potassium uptake. Potassium use in farmers' plots ranged from 44 to 63 kg K ha^{-1} and fertilizer potassium use was 4–21 kg less in site-specific nutrient management treatments compared with farmers' plots. Lower fertilizer use rates in site-specific nutrient management plots resulted from model-based predictions that accurately accounted for the high native soil fertility status measured as plant nutrient uptake in omission plots. Pathak *et al.* (2003) made modifications in the QUEFTS model for its use in wheat in rice–wheat systems in South Asia. A relationship between potassium uptake in minus potassium plots, a measure of soil potassium supply and exchangeable soil potassium was established. The required potassium accumulation by wheat for 1 ton grain yield was 28.5 kg. A preliminary validation of the model in wheat showed good agreement with grain yield values observed and predicted by the model, indicating that the model can be used for predicting fertilizer recommendations to achieve a yield target of wheat. Estimated potassium requirement (kg per ton grain yield) using the QUEFTS model ranged from 14.5 to 15.7 kg for rice (Witt *et al.*, 1999) and 28.5 to 32.0 kg for wheat (Pathak *et al.*, 2003). Site-specific nutrient management has potential for improving yields and nutrient use efficiency in irrigated rice–wheat systems to close existing yield gaps.

E. POTASSIUM USE AND RESISTANCE TO DISEASE AND PEST INCIDENCE

Potassium has been known to impart resistance against diseases and a high concentration of K ions in the cell sap restricts attack by insects. Reviewing relationships between use of potassium fertilizers and incidence of plant diseases, Perrenaud (1977) observed that potassium reduced bacterial and fungal diseases in 70% of instances, insects and mites 60% and nematodes and virus influences in the majority of the cases. Influence of potassium on crop yields varied according to the parasite group, as accumulating nitrogen compounds and sugars are frequently accompanied by improved conditions for parasite development. Since tissue hardening and stomatal opening patterns are closely related to infestation intensity, nitrogen balance with potassium is significant to disease susceptibility. Vaithilingam and Baskaran (1985) examined the mechanism of induced resistance to insect pests in rice plants with enhanced potassium application and observed that rice plants receiving high amounts of potassium accumulated more total phenols and ortho-dihydroxy phenols. Accumulation of phytophenols which are the precursors for synthesis of several toxic compounds in the plant system render the plant resistant to pests. Further, it was found that the amino nitrogen content, which is the basic dietary requirement of many insect species, was drastically reduced at high potassium dose in the tested rice plants. Increase in lignification and scleranchymatous layer in rice supplied with adequate potassium fertilizers also acts as a mechanical barrier to pest invasion in potassium treated soils. Prasad and Misra (1983) observed that the population of hoppers in rice was significantly higher in no-K plots than in potassium treated ones receiving the same level of nitrogen and phosphorus. Mondal and Mia (1985) studied the effect of potassium application on bacterial blight by inoculating rice plants with *Xanthomonas campestris* at maximum tillering and at flag leaf stage. The results (Table XVII) showed that average lesion length was significantly lower in potassium treated series than on soils to which less potassium was applied.

Table XVII
Effect of Potassium Application on the Response of Rice to Bacterial Blight Inoculation

K level (mg K kg^{-1} soil)	Average lesion length (cm)	
	Inoculation at maximum tillering stage	Inoculation at flag leaf stage
100	30	13
183	22	8
266	20	6
349	19	6
432	16	5

Source: Mondal and Mia (1985).

VII. POTASSIUM BALANCE IN SOIL–PLANT SYSTEMS

Introduction of modern production technologies for rice and wheat with high nitrogen responsive high yielding varieties has resulted in increased annual removal of potassium by above-ground portions of the crops. Long-term studies have indicated that continuous rice–wheat cropping will lead to depletion of potassium in soil even when optimum levels of fertilizer potassium have been applied. From the nutrient removal data (Table IX) it is evident that annual removal of potassium by rice–wheat cropping system equals or exceeds that of nitrogen, while the replacement of potassium by fertilizer represents only a fraction of nitrogen (Table II). Furthermore, most of the potassium uptake in rice and wheat crops is stored in straws, which is mostly removed from the field as animal feed and is not directly returned to the soil.

Long-term studies have shown that potassium balance in rice–wheat system is highly negative even when recommended doses of potassium are applied to rice–wheat cropping system. Data obtained from two long-term experiments at Ludhiana in western India and Bhairahawa in Nepal (Table XVIII) shows that highly negative potassium balance in NPK treatments was substantially improved by application of farmyard manure or returning wheat residues. In Fig. 2 are shown potassium balances from two long-term experiments in middle- and lower Gangetic plains in which treatments consisted of increasing levels of NPK (Nambiar and Ghosh, 1984). Interestingly at Barrackpore in West Bengal, higher potassium levels applied due to smectitic nature of clay minerals resulted in potassium balance ranging from 0 to -75 kg K ha^{-1}. In sharp contrast, potassium balances in illitic soils in Pantnagar were highly negative even under 150% NPK treatment as removal of potassium by rice and wheat was high even at low potassium application levels (Fig. 2). In a long-term experiment at Ludhiana,

Table XVIII
Annual Potassium Balance in Two Long-term Experiments Progressing at Ludhiana, Northwestern India and Bhairahwa, Nepal in the Indo-Gangetic Plains

	Input (kg K ha^{-1} yr^{-1})				Output (kg K ha^{-1} yr^{-1})		
Treatment	Manure/ Fertilizer	Irrigation	Rain	Seed	Crop removal	Leaching loss	Balance (kg K ha^{-1} year^{-1})
Rice–rice–wheat long-term experiment at Bhairahwa, Nepal (1978–98)							
Control	0	20.4	5.0	4.9	36.4	6.0	−12.1
NPK	75	20.4	5.0	4.9	150.3	17.3	−62.3
FYM	120	20.4	5.0	4.9	148.8	16.7	−15.3
Rice–wheat long-term experiment at Ludhiana, India (1988–2000)							
NPK	50	100	5.0	2.7	285	19	−151
Wheat straw + NPK	111	100	5.0	2.7	281	28	−90
FYM + NPK	131	100	5.0	2.7	271	31	−63

Source: Regmi *et al.* (2002b); Yadvinder-Singh *et al.* (2003a).

net negative potassium balance of more than 200 kg K ha^{-1} year^{-1} was observed when no potassium was applied to rice or wheat (Table XIX). Application of fertilizer potassium to rice, wheat or both resulted in less negative potassium balance. Removal of all the straw from the fields leads to potassium mining at alarming rates because 80–85% of the potassium absorbed by rice and wheat crops is in the straw. At Rangpur in Bangladesh, potassium balance in a rice–mungbean–wheat rotation ranged from −152 to −98 kg K ha^{-1} with total

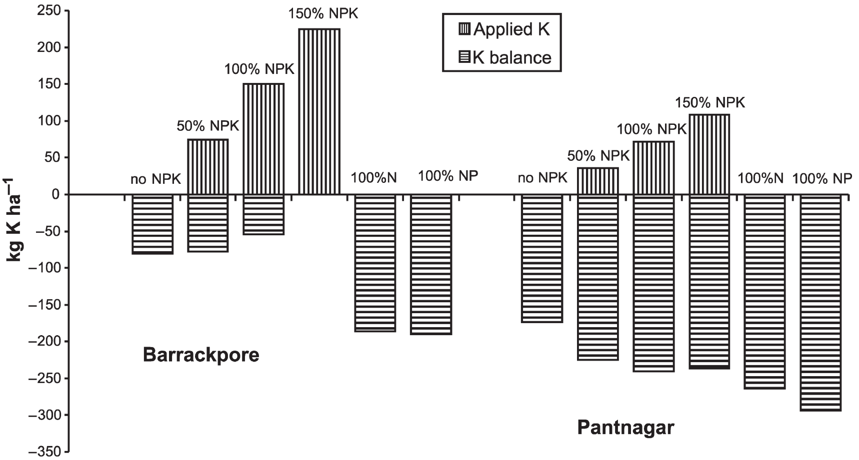

Figure 2 Potassium balance (applied minus removed by rice and wheat) in different treatments in long-term experiments at Barrackpore and Pantnagar [adapted from Nambiar and Ghosh (1984)].

Table XIX
Annual Potassium Balance (Applied as Fertilizer Minus Removed by Plants) as Influenced by Direct, Residual and Cumulative Application of Potassium in a Rice–Wheat System at Ludhiana in Northwestern India

K applied (kg K ha^{-1})		Mean grain yield of rice (1990–2000) (t ha^{-1})	Mean grain yield of wheat (1990–2000) (t ha^{-1})	Mean annual K balance (kg K ha^{-1})
Rice	Wheat			
0	0	5.30	4.70	−215
0	25	5.36	4.90	−198
0	50	5.38	5.02	−182
0	75	5.45	4.98	−162
25	0	5.32	4.87	−211
50	0	5.42	4.75	−188
75	0	5.53	4.84	−173
25	25	5.39	4.96	−202
50	50	5.59	5.07	−161
75	75	5.53	4.97	−103

Source: Bijay-Singh, Yadvinder-Singh and C.S. Khind, Department of Soils, Punjab Agricultural University, Ludhiana, India; unpublished data.

potassium application to the system ranging from 33 to 83 kg K ha^{-1} (Abedin and Mukhopadhay, 1990). It may be interesting to note that potassium rates applied by most farmers are lower than those used in the long-term experiments.

Ladha *et al.* (2003) analyzed 33 rice–wheat long-term experiments in the Indo-Gangetic plains of South Asia, non-Indo-Gangetic plains in India, and in China to monitor yield trends, and identify possible causes of such yield trends. In treatments where recommended rates of nitrogen, phosphorus and potassium were applied, yields of rice and wheat stagnated in 72 and 85% of the long-term experiments, respectively, while 22 and 6% of the long-term experiments showed a significant ($P < 0.05$) declining trend for rice and wheat yields, respectively. In over 90% of the long-term experiments, the fertilizer potassium rates used were not sufficient to sustain a neutral potassium input–output balance (Fig. 3). All the long-term experiments with a significant yield decline had large negative balances of potassium. The potassium balances were consistent with the changes in soil potassium status in the Ludhiana and Bhairahwa long-term experiments. In these two experiments, soil potassium declined by 62 and 33%, respectively, after 10 years of cultivation (Bhandari *et al.*, 2002; Regmi *et al.*, 2002b). Similar observations were made by Dawe *et al.* (2000), Duxbury *et al.* (2000), and Yadav *et al.* (2000a) in rice–wheat systems. Xie *et al.* (1991) have reported negative potassium balance in different regions of China, where rice–wheat cropping system is predominantly practised (Table XX). In a study based on several on-farm locations under rice–wheat cropping system in Jiangsu and Sichuan provinces of

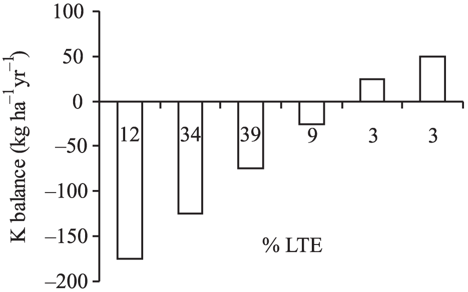

Figure 3 Apparent K balances in rice–wheat cropping systems. Long-term experiments (LTE) in Asia [adapted from Ladha *et al.* (2003)].

China, negative potassium balances were observed in the range of −160.6 to −12.0 kg K ha^{-1} (Table XXI) (Zhou *et al.*, 2000). In a Vertisol, 33 kg K ha^{-1} was applied to rice as well as wheat grown in a sequence for 8 years (Yadvinder-Singh *et al.*, 2002a). Application of increasing levels of fertilizer N resulted in an increase in the negative potassium balance from 56 kg K ha^{-1} in no-N control to 103 kg K ha^{-1} at 90 kg N ha^{-1} and 156 kg K ha^{-1} at 180 kg N ha^{-1}.

The negative potassium balances mean that it will be impossible to maintain the present production levels of the rice–wheat system. Results from long-term fertility experiments in India show that crop response to potassium application start appearing over a period of time in soils which were initially well supplied with potassium (Nambiar and Ghosh, 1984). Such responses to potassium started appearing after 3 years in rice and 11 years in wheat at Pantnagar (Uttar Pradesh) and after 3 and 7 years, respectively, at Barrackpore (West Bengal). Long-term studies suggest that application of farmyard manure and recycling of crop residues can help improve the potassium balance in the rice–wheat cropping system. There is,

Table XX
Potassium Balance in Different Regions of China where the Rice–Wheat Cropping System is Predominantly Practised

Regions	K balance (kg K ha^{-1} year^{-1})
Purplish fluvo-aquic soil around Donting Lake, Jiangxi	−153
Guizhou	−30
Hang Jia Hu plain	−38
Jiangsu	−90
Taihu Lake region	−62

Source: Xie *et al.* (1991).

Table XXI
Potassium Balance in the Soil under Rice–Wheat Cropping Systems at Several On-farm Locations in Jiangsu and Sichuan Provinces in China

County and Province	Number of on-farm locations	Potassium balance (kg K ha^{-1})
Siyang, Jiangsu	18	−12.0
Qidong, Jiangsu	20	−48.4
Changshu, Jiangsu	18	−87.1
Chongzhou, Sichuan	30	−75.7
Fushun, Sichuan	27	−66.0
Jianyang, Sichuan	29	−160.6

Source: Zhou *et al.* (2000).

however, a need to work out long-term potassium balances in the rice–wheat system based on precise data on potassium removal from a field or region through straw, potassium inputs from irrigation or rain water besides the well-defined inputs and outputs such as fertilizers, manures, and grains. Straw management can strongly influence potassium budgets and can help in efficient management of potassium for a sustainable rice–wheat system in the Indo-Gangetic plain.

VIII. CHANGES IN POTASSIUM FERTILITY IN THE SOIL UNDER RICE–WHEAT CROPPING SYSTEMS

Deficiency of potassium in the Indo-Gangetic plain is not as wide spread as nitrogen and phosphorus but soils testing high with respect to available potassium some years ago are becoming potassium-deficient due to heavy removal by rice and wheat and inadequate potassium application. Since depletion of soil potassium reserves is a matter of deep concern from the point of view of sustainability of rice–wheat system, it is important to analyze the data from long-term experiments so as to plan efficient management of both potassium fertilizers and soil potassium reserves. In six out of eight benchmark soil series in the Indo-Gangetic plain studied by Sekhon *et al.* (1992) for detailed characterization of potassium, measurements were made again after 10 years to assess changes in potassium fertility of soils. The data pertaining to changes in ammonium acetate and HNO_3 extractable potassium are listed in Table XXII. Both the indices show considerable decrease in availability of potassium in a span of 10 years thereby suggesting that crops may start responding to potassium fertilizer in course of time. Tiwari (1985) observed a decline in available potassium and non-exchangeable by 17% and 2.8% after two cropping cycles measured on 14 fields at Kanpur (middle Indo-Gangetic plains). In long-term experiments progressing

Table XXII
Changes Observed in Potassium Fertility in some Soil Series in Rice–Wheat Growing Regions of the Indo-Gangetic Plains

	Ammonium acetate-K (mg kg^{-1})		HNO_3-K (mg kg^{-1})	
Soil series and location	First sampling	After 10 years	First sampling	After 10 years
Nabha, Ludhiana, Punjab	104 ± 54	63 ± 41	965 ± 255	875 ± 230
Akbarpur, Etah, Uttar Pradesh	125 ± 41	71 ± 23	1448 ± 203	1231 ± 188
Rarha, Kanpur, Uttar Pradesh	95 ± 33	79 ± 20	1531 ± 353	1497 ± 180
Hanrgram, Bardhaman, West Bengal	132 ± 53	93 ± 16	425 ± 160	400 ± 191
Kharbona, Birbhum, West Bengal	42 ± 17	29 ± 16	119 ± 34	109 ± 26

Source: Sekhon (1999).

at different locations in the Indo-Gangetic plain, a decrease in available potassium has been observed at all sites in treatments where no potassium has been applied during 13 to 14 year period (Table XXIII). Except at Ludhiana, a decrease in available potassium content of soil was noticed even in treatments receiving potassium for both wheat and rice. These data suggests that fertilizer

Table XXIII
Changes in Available Potassium in Soils in Different Treatments (no NPK, 50% NPK, 100% NPK, 50% NPK + FYM, 50% NPK + Crop Residues, 50% NPK + Green Manure) in Long-term Fertility Experiments on Rice–Wheat Systems at Various Locations in the Indo-Gangetic Plains

		1M ammonium acetate extractable K (mg kg^{-1})	
Location	Duration of the experiment	At beginning	After 12–15 years
Ludhiana	1983–84 to 1997–98	46	4–17% increase (except in no NPK treatment)
Pantnagar	1983–84 to 1997–98	65	17–34% decrease
Kanpur	1985–86 to 1997–98	82	10–22% decrease
Faizabad	1984–85 to 1997–98	161	10–30% decrease
Sabour	1984–85 to 1997–98	58	7–14% decrease except in 50% NPK + FYM treatment

100% NPK = 120 kg N + 26 kg P + 33 kg K ha^{-1}.
Source: Yadav *et al*. (2000a).

doses considered as optimum can still result in potassium depletion from the soil at high productivity levels and in the process become sub-optimal doses.

In rice–wheat system, potassium is readily displaced from the exchange complex due to increased concentrations of Fe (II), Mn (II) and ammonium during flooding phase (rice) (Ponnamperuma, 1972). Though the displacement of potassium from the exchange complex ceases during aerobic phase (wheat), Kadrekar and Kibe (1973) and Singh and Ram (1976) have shown that alternating wetting and drying increases the availability of exchangeable potassium in the soil. Nevertheless, as discussed by Dobermann *et al.*, (1996a) for a Pantnagar soil, perhaps due to unfavourable ratios of potassium to other cations (Ca, Mg, Fe) in the soil, potassium nutrition of rice–wheat system in the Indo-Gangetic plains is not assured. The rapid decline in plant available potassium after flooding of dry soil (Cassman *et al.*, 1995; Olk *et al.*, 1995) some what similar in mineralogy to those found in the Indo-Gangetic plain contrast with the general view that flooding a soil increases the solution potassium.

Rice–wheat cropping system has tremendous capacity to draw large quantities of potassium and soils are often the exclusive suppliers of potassium nutrition to plants in the Indo-Gangetic plains. Warning signals are already emanating from present potassium management practices with respect to sustainability of the system as soil deterioration with respect to potassium supplying power is being largely overlooked. About a quarter century ago, Singh and Brar (1977) could show that continuous cropping without potassium dressing decreased 1M ammonium acetate extractable potassium in a soil from trans-Gangetic plains in Northwest India from 165 to 85 kg ha^{-1}. Still there was no response of crops to potassium application; obviously 90% of potassium demand was met by release of potassium from non-exchangeable pool. In a 8-year experiment on a Vertisol, Singh *et al.* (2002b) applied 33 kg K ha^{-1} to both rice as well as wheat and in view of a large negative potassium balance found sustainability of the system at threat as a distinct depletion of potassium from the sum of changes in $HNO_3 + HClO_4$ extractable potassium after 8 years (16 crops) in 0–15, 16–30, and 31–45 cm layers was observed. In no-N treatment, the total depletion of potassium was 54 kg K ha^{-1} year^{-1}, and it increased to 102 and 145 kg ha^{-1} year^{-1} on application of 90 and 180 kg N ha^{-1} to rice. In the 20-year long-term experiment at Bhairawah, Nepal, total potassium showed a significant decline in the NPK and FYM treatments over the last nine years of the experiment (Regmi *et al.*, 2002b). During the first 10 years as well (when no soil analyses were made), a greater potassium extraction from soil may have occurred because of higher biomass removal. The FYM treatment had significantly higher total soil potassium than the control and NPK treatments in four out of seven sampling years (Fig. 4a). But when extracted with ammonium acetate, the potassium pool did not differ among treatments (Fig. 4b). The average annual decline of total potassium was 180 and 92 mg kg^{-1} in the NPK and FYM treatments, respectively. It suggests that the application of 25 and 40 kg K ha $^{-1}$crop^{-1} in

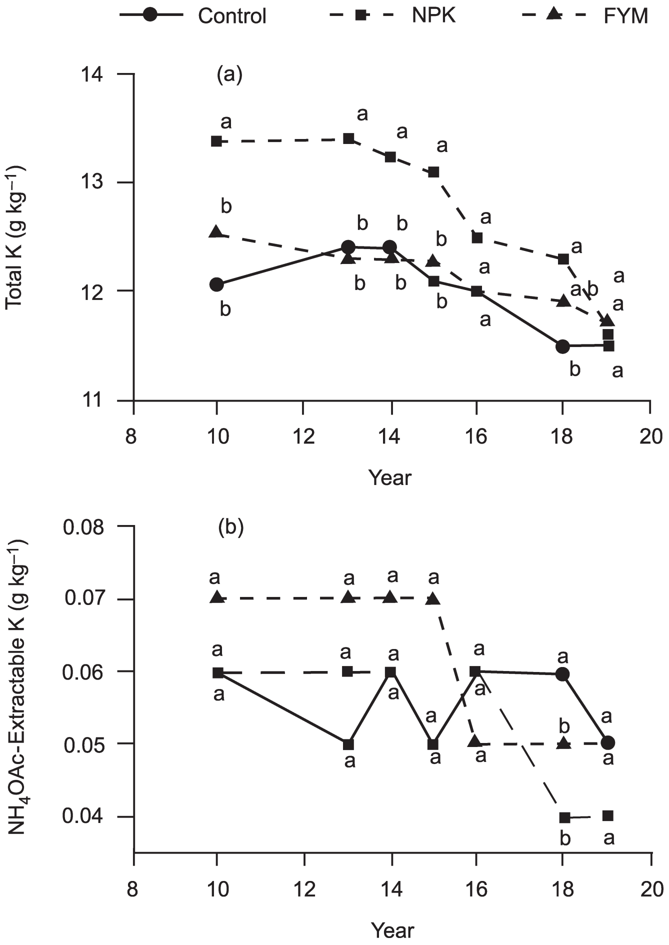

Figure 4 (a) Total soil K and (b) ammonium acetate extractable K in control, NPK, and farmyard manure (FYM) treatments of the long-term plots maintained at Bhairawah, Nepal after 10, 13, 14, 15, 16, 18, and 19 years. Different letters indicate significant differences between treatments within a year at $P < 0.05$ [adapted from Regmi *et al.* (2002b)].

the NPK and FYM treatments, respectively, was not sufficient to maintain the soil potassium level in the rice–rice–wheat rotation and should also lead to irreversible adverse changes in soil potassium pools.

The negative K-balance has serious implications on mineralogy of potassium in soils under rice–wheat cropping system in the Indo-Gangetic plains. Due to incorporation of potassium through canal and tube well water containing substantial amounts of potassium, weathering of potassium containing minerals, particularly

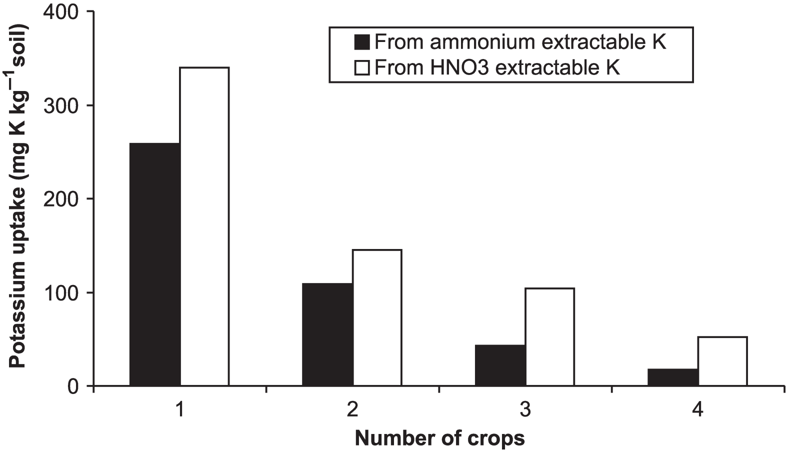

Figure 5 Mean potassium uptake by rice from ammonium acetate and HNO_3 extractable K fractions of soils as influenced by continuous cropping from 26 soil types in different parts of China [adapted from Xie and Li (1987)].

illite is minimal. Mukhopadhyaya *et al.* (1992) observed formation of edge-wedge sites in potassium bearing minerals when K^+ was removed through 18 successive crops. After 28 crops, there was about 1% conversion of illite to vermiculite. The X-ray diffractograms of 1.0 nm peaks showed broadening towards low angle suggesting loss of interlayer K^+. A co-occurrence of illite and vermiculite indicated that in spite of potassium incorporation through irrigation, crop residues and fertilizers, the minerals exist under K^+-loss domain. The scenario is alarming in view of advancement of weathering font in illite–vermiculite or illite–vermiculite–smectite phases. In China, most of the soils under rice–wheat system are already in kaolinite and vermiculte–smectie phases and thus application of potassium leads to increased yields of both rice and wheat. Exhaustion experiments conducted on 26 soil collected from different parts of China revealed that with just four continuous crops of rice (no potassium was applied) potassium uptake by crops was drastically reduced and 60–80% potassium absorbed by crops came from slowly available potassium (HNO_3 extractable potassium) (Fig. 5). Negative potassium balances in these soils further suggest that potassium application rates will have to be increased to sustain high production levels in the rice–wheat systems and to avoid further aggravating the situation.

IX. RESEARCH NEEDS

The soil moisture regimes in rice–wheat system show tremendous variation but the effects of such moisture changes on potassium availability and crop responses have not received much attention. Research is needed to clarify processes of fixation and release of potassium during drying and wetting cycles, and extent of impeded potassium diffusion in the rhizosphere of rice and its effect on potassium uptake at very high yield levels. A better understanding is needed of the processes affecting long-term fate of fertilizer potassium in irrigated rice–wheat system, including more information on the recovery and leaching of potassium (Dobermann *et al.*, 1998).

There exist a large number of publications on forms of potassium, availability in soils and response of rice and wheat to potassium application. Most of these publications will become redundant for future planning if matching information about soil mineralogy is not available. To work out management practices for achieving sustainable rice–wheat cropping systems in the Indo-Gangetic plains and in China, it will be necessary to understand potassium availability in the context of mineralogical composition of the soils. Research should be initiated to predict the time taken for soils currently well supplied with potassium for rice and wheat to become deficient in potassium and it should be backed-up by adequate input from the clay mineralogical investigations.

The critical limits distinguishing soils that are likely to profit from supplementary application of potassium from those which are not, are currently uniform for all the soils in both Indo-Gangetic plains and in China. The differences in mineralogy and forms of potassium provide strong indications regarding desirability of different sets of critical limits. Research should be able to propose and test the most appropriate sets of such limits. Dynamic soil test methods assaying the potassium supplying power of soils under rice–wheat system should be developed. An integrated approach to potassium fertilizer recommendation may be developed based on site factors, laboratory analysis (texture, exchangeable and non-exchangeable), and data from weather records, soil survey (clay mineralogy, soil depth), probable yield and crop response, and processed by computer models that would generate a fertilizer recommendation derived almost entirely from site-specific data.

In view of imbalanced use of nitrogen, phosphorus and potassium in rice–wheat cropping system in both South Asia and China, adequate data are not available on rates of potassium depletion due to continuous applications of nitrogen with or without phosphorus or potassium. Interaction of potassium with other nutrients including micronutrients also needs to be studied more thoroughly. Data on interactions of potassium with other nutrients and inputs can help improve strategies for the integrated management of different inputs. Models for estimating crop nutrient requirements based on interactions of N and potassium and for predicting the long-term fate of added potassium fertilizers should be developed for rice–wheat system. These may provide a basis for introducing farm or field-specific nutrient management approaches.

Sufficient information is not available on the positive impact of potassium in improving grain quality of rice and wheat. Role of potassium in combating disease and pest incidence in rice–wheat system has also not been adequately researched. Information needs to be generated on potassium dynamics and long-term responses of rice and wheat to applied potassium in changing scenario of tillage systems, such as increasing adoption of minimum/zero tillage in wheat and direct seeding of rice involving no puddling.

Applied research must provide the tools necessary for practical use of long-term strategies for potassium management based on nutrient balance concept. It should be useful to develop potassium balance sheets for all typical soils under rice–wheat cropping system. This will need adequate data on the gross and net contributions from irrigation water, crop residues, organic manures, and removals through runoffs and erosion. Soils, most off-balance should receive particular attention for studies on potassium needs of rice–wheat cropping system.

Recycling of crop residues and other organic inputs influence nutrient supplying capacity of the soil. We need an improved understanding of how crop residue management affects potassium cycling and different pools of potassium in the soil. This will facilitate the development of budgets to balance potassium removal with nutrient application of potassium at different yield targets which seems necessary in sustainable, high yielding rice–wheat production systems. In long-term experiments, potassium is being continuously applied in some plots but still there is no buildup of available potassium. Research philosophy in long-term experiments should be more analytical rather than exploratory and documentary. Also, to obtain a more meaningful picture of the changes taking place in the soil potassium status in much of the root zone, soil layers deeper than 0–15 cm should be taken into account.

X. CONCLUSIONS

A better understanding of soil potassium in relation to productivity is immensely important to develop sustainable rice–wheat cropping systems in the Indo-Gangetic plains and in China. Due to nitrogen remaining heavily subsidized, there exists a continued imbalance in the use of nitrogen, phosphorus and potassium fertilizers. Farmers in the Indo-Gangetic plains apply very small amount of potassium fertilizers to rice–wheat cropping systems as compared to those in China.

Most of the soils in the Indo-Gangetic plain contain illite as dominant clay mineral and are medium to high in ammonium acetate (1M, pH 7.0) extractable potassium. Therefore, responses of rice and wheat to applied potassium are generally small. Total annual potassium removal by rice–wheat system exceeding 200 kg K ha^{-1} and negligible fertilizer potassium application are causing depletion of soil potassium supply. Alluvial soils in most of the Indo-Gangetic plain are less weathered and potassium availability deciphered through ammonium acetates extractant was rarely low, although the suitability of ammonium acetate extractable potassium as an index of plant available potassium for different soils varying in texture and clay mineralogy remains controversial. Rate and extent of release of non-exchangeable potassium play a crucial role in meeting the potassium requirements of the rice–wheat cropping systems. Continuous negative potassium balances (applied through fertilizers minus removal by crops) mean soil potassium mining and ultimately loss in soil fertility and it will be impossible to maintain the present production levels of the rice–wheat system. Potassium balances worked out after taking into consideration management of straw and potassium inputs from irrigation water may, however, suggest means and ways to achieve sustainability of rice–wheat cropping system.

Soils under rice–wheat system in China contain clay minerals that are at more advanced stage of weathering than illite. Thus responses of both rice and wheat are substantial as compared to in the Indo-Gangetic plains. However, farmers are not able to apply amounts of fertilizer potassium equal to or more than the removal of potassium by the rice–wheat system. Measure of slowly available potassium based on HNO_3 extraction of soils is thus a reliable index of potassium availability in Chinese soils. Continuous negative potassium balance is possibly accelerating the depotassification and weathering of clay minerals and as a consequence, large dressings of potassium fertilizers will be required to meet the requirements of rice–wheat cropping system at high productivity levels.

The activity of K^+ ions in soil solution around mica particles is a factor in determining the release of potassium from the micas. Thus, leaching as well as potassium removal by rice and wheat in large quantities enhances release of potassium from micas by removing the reaction products and accelerates the transformation of micas to expansible 2:1 layer silicates and other weathering products. Keeping in view the existence of illite–vermiculite, illite–vermiculite–smectite or illite–smectite/chlorite–kaolinite phases, the hidden hunger for potassium and more importantly farm practices leading potassium development vis-à-vis weathering of potassium minerals in the trans-, upper- and middle Gangetic plain to a point of no return may soon pose a great threat. Clay minerals in Chinese soils being already in smectite/chlorite-kaolinite phase of weathering, are creating unfavorable situations with respect to potassium nutrition of rice–wheat cropping system.

Conventionally, blanket fertilizer potassium recommendations are often made for over large areas without taking into account the wide variability in soil nutrient supplies, fertilizer efficiency, and site- and season-specific crop nutrient requirements within each recommendation domain. This is not adequate to sustain higher yields and maintain or build-up soil fertility at a level that ensures maximum efficiency from potassium inputs. In this context, interaction of potassium with other nutrients and inputs is also important. It is argued that a sustainable fertilizer management strategy must ensure high and stable overall productivity with optimum economic return and sufficient nutrient supply for potential yield increases with minimal leakage of nutrients into the environment. This can be achieved if exogenous potassium supply is matched with the nutrient supplies from soil and crop demand.

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