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Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. I. Potassium uptake and K balance

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Abstract

Research in many countries indicates a negative K balance in intensive, irrigated rice systems but comparative studies across different environments are few. Using a uniform sampling methodology, we measured K uptake, K use efficiency, and K balance in six different fertilizer treatments of long-term fertility experiments with rice at 11 sites in five Asian countries. Depending on the absolute yield level, K uptake requirements of rice ranged from 17 to 30 kg K per ton of grain. For yields greater than 8 t ha^{-1}, total K uptake exceeded 200 kg ha^{-1}. The K balance at most experimental sites was negative, with an average net removal of 34–63 kg K $season^{-1}$. There was significant depletion of soil K reserves at many sites. Based on these data, we estimated that the amount of K cycled annually from the soil into rice plants is 7–10 million t in irrigated rice systems of Asia. About 1 million t of this total amount is removed with the harvested grain. Present recommendations for K addition in most intensive irrigated rice domains are insufficient to replace K removal. However, response to K can only be expected on soils with deficient supply capacity and where other nutrients, particularly N and P, are not limiting. Efficient K management for rice must therefore be based on the K input/output balance, the achievable yield target, and the effective K-supplying power of the soil.

Introduction

The introduction of modern rice production technologies based on early-maturing, N-responsive, semidwarf varieties has increased both the cropping intensity (double- and triple-crop rice systems) and rice yields in the irrigated lowlands of Asia. Although the Green Revolution had tremendous impact on N fertilizer use in Asia, it had much less impact on the use K fertilizers. Most soils of the alluvial floodplains in Asia were generally regarded as high in extractable K, and it was thought that additional K supply from irrigation water would make K a rare limiting factor in irrigated rice systems [Bajwa, 1994; De Datta et al., 1985; Kawaguchi; 1977]. However, the seasonal and annual crop demand for K has increased markedly and K balances have shifted towards the negative side [De Datta et al., 1985; Uexkuell, 1985]. Potassium deficiency is now more widespread even on heavy-textured soils. Examples include alluvial, illitic soils in India [Tiwari, 1985], lowland rice soils of Java, Indonesia [Sri Adiningsih et al., 1991], and vermiculitic clay soils of Central Luzon, Philippines [Oberthuer et al., 1995].

Agriculture in Asia depends heavily on indigenous soil K resources and fertilizer K imports. Recoverable K reserves in South and Southeast Asia account for only 7.5% of the world K reserves [Sheldrick, 1985]. Production of manufactured K_2O fertilizers in 1993 was 0.4% of the total world production and regional imports (excluding Japan) amounted to 3.6 x 10^6 t K_2O, or 24% of the world total [Maene, 1995]. Potassium use in Asian agriculture is low and decisions by rice farmers about K application mostly depend on personal preferences, fertilizer market conditions, or government regulations, rather than on knowledge of the soil K supply characteristics and crop demand.

Because more than 90% of total root length of rice is located within the topmost 0–20 cm soil [De Datta et al., 1988a; Teo et al., 1995], long-term strategies for K management in intensive, irrigated rice systems must focus on maintaining soil fertility in this layer to increase root uptake rates by creating adequate buffering power and K concentrations in solution. A quantitative understanding of the nutrient balance and soil nutrient-supplying power will provide information needed to develop improved nutrient management strategies for optimizing yields, net returns, and maintenance of the soil resource base in the long run. Negative K balances under intensive rice cropping have been reported from of southern China [Huang et al., 1990], India [Mohanty et al., 1989; Prasad, 1993], and Bangladesh [Abedin et al., 1991], but no comparative studies across different soils and agroecological zones are known to us. There is also considerable uncertainty about crop K requirements, because estimates range from 16 to 47 kg K t^{-1} of rough rice [Goswami et al., 1978].

In this paper, we present some recent multi-national research on K requirements of irrigated rice systems, aiming at a better understanding of the primary factors affecting crop K demand and soil K supply. We will first examine the relationship between total K uptake and grain yield as a yardstick for assessing K requirements of the rice crop. We will then examine the K balance in long-term fertility experiments (LTFE) with rice in five countries and the implications for soil and crop management. In part II [Dobermann et al., 1996], we will assess soil testing approaches for characterizing the K-supplying capacity of rice soils.

Material and Methods

Long-term fertility experiments with rice

The first long-term experiment on modern rice production systems in the tropics was established at IRRI in 1964 to quantify changes in soil fertility and rice yield in response to N, P, and K fertilizer inputs in a continuous double-crop rice system (Table 1). Starting in 1977, international cooperative trials on soil fertility and fertilizer management were organized by a network which later became known as INSURF (International Network on Soil Fertility and Sustainable Rice Farming). Long-term fertility experiments were initiated using eight standard fertilizer treatments (Control, +N, +P, +K, +PK, +NP, +NK, +NPK) with similar rates of fertilizer application. These experiments provided valuable data for assessing effects of fertilizer application on rice yield under very different climatic and soil conditions. Unfortunately, at many sites, only grain yield was measured continuously, whereas changes in soil fertility status or nutrient uptake by rice were measured only occasionally or not at all.

In collaboration with the national agricultural research systems (NARS) scientists participating in the INSURF project, we measured soil properties and nutrient uptake at 11 LTFE sites in Asia in 1993 (Table 1). A double-crop rice system was practiced at most sites. Treatments of different N, P, and K fertilizer combinations and an unfertilized control were arranged in a completely randomized block design with three or four replicates. Plot sizes ranged from 28 to 36 m^2 and permanent bunds were placed between the plots to avoid carry over effects of soil and nutrients. Rice was transplanted at all sites and grown in submerged soil with irrigation. Control measures were applied as required to avoid yield losses from weeds and insects. However, the NP treatment at Lanrang (Indonesia) was affected by serious rat damage and results obtained from this site were not included in the K balance analysis. The rice varieties used at each site represented the best-performing varieties at each location.

Sampling and analyses

In 1993, at each of the 11 sites four soil cores were taken from the 0–20 cm puddled soil layer in each treatment plot before maximum tillering (20–30 d after transplanting). The four cores from each plot were pooled and mixed thoroughly into a homogeneous soil paste. One half of this pooled sample was air-dried, sieved through 2 mm, and used for determination of standard soil properties. The other half was used to measure K release kinetics from anaerobic soil using ion exchange resin capsules, as described in part II. On air-dried soils particle size (pipette method), organic C (Walkley-Black), total N (Kjeldahl), pH (H_2O), CEC and exchangeable bases (NH_4OAc method), extractable P (Olsen and Bray I), 0.05 N HCl extractable Zn, hot-water extractable B, and dithionate-citrate extractable Fe and Mn were determined using standard procedures [Ponnamperuma et al., 1981; van Reeuwijk, 1992]. The CEC of the clay fraction was calculated assuming an average CEC of soil organic mater of 350 cmol kg^{-1} and using equations given by Van Reeuwijk (1992). To minimize sampling and analytical errors, all samples were collected by the same researchers and analyzed by IRRI's Analytical Service Laboratory.

Table 1. Soil types, soil properties, cropping system, and fertilizer rates in the long-term fertility experiments monitored in 1993.

Site Province	Year of initiation	Soil classification	Texture	Clay	Org. C	CEC	CEC^{2}_{clay}	pH	Cropping system	Fertilizer rates[3] N	P	K
				%	g kg^{-1}	— cmol kg^{-1} —				—kg ha^{-1}—		
Philippines												
IRRI Laguna	1964	Andaqueptic Haplaquoll	C	54	21	34	49	5.9	Rice-rice[4]	200	25	40
PhilRice Nueva Ecija	1968	Entic Pellustert	SiC	40	13	29	59	6.6	Rice-rice[4]	200	25	100
BRIARC Camarines Sur	1968	Typic Pelludert	C	53	18	27	39	6.7	Rice-rice[4]	200	25	40
Indonesia												
Maros S. Sulawesi	1977	Typic Tropaquept	C	51	21	30	44	6.3	Rice-rice[4]	120	17	33
Lanrang S.Sulawesi	1977	Aeric Fluvaquent	CL	27	10	14	38	6.0	Rice-rice[4]	120	17	33
Vietnam												
Cuu Long Hau Giang	1988	Fluvaquentic Humaquept	C	57	26	20	18	5.7	Rice-rice[5]	80	17	25
China												
Shipai Guangzhou	1983	Paddy soil, aremaceous rock[1]	CL	29	9	6	8	6.0	Rice-rice[5]	120	17	33
Jinxian Jiangxi	1981	Paddy soil, quaternary period, red soil[1]	SiCL	32	13	7	6	5.9	Rice-rice[5]	90	19	62
Qingpu Shanghai	1983	Paddy soil, river alluvium[1]	SiCL	28	16	16	39	7.2	Rice-wheat[5]	120	17	33
India												
Pantnagar Uttar Pradesh	1984	Fluventic Haplaquoll	SiL	25	9	12	35	8.5	Rice-wheat[5]	120	17	33
Coimbatore Tamil Nadu	1988	Vertic Ustropept	C	43	7	27	59	8.2	Rice-mungbean -sesame[5]	100	21	41

[1] Based on Chinese soil classification.
[2] CEC_{clay} = (CEC-0.35org.C)*100/clay. This equation assumes an average CEC of soil organic matter of 350 cmol kgC^{-1} (Van Reeuwijk, 1992).
[3] P and K are incorporated into the soil basally, N is applied in three equal splits: basal, midtillering, and first flowering; the basal application is incorporated into the soil. At PhilRice, NK receives 50 kg K ha^{-1}, NPK receives 100 kg K ha^{-1}.
[4] Remaining stubble incorporated into soil.
[5] All straw removed (cutting at ground level).

At maturity, straw and grain weight were measured from a 6- or 12-hill sample after oven-drying to constant weight at 70 °C. Hills included all aboveground biomass. Plot grain yield (adjusted to 14% moisture content) was determined in a 5-m^2 harvest area. Oven-dried straw and grain from the hill samples were ground for plant analysis. Potassium concentrations in plant tissue were determined using an atomic absorption spectrophotometer after soaking dried plant material in 1 N HCl for 24 h [Yoshida et al., 1976]. Total uptake K was calculated from the grain yield of the 5-m^2 harvest area adjusted to oven-dry yield, from oven-dry straw yield estimated from the oven-dry harvest index of the hill sample and the oven-dry grain yield of the

5-m^2 harvest area, and from nutrient concentrations in the grain and straw from the hill sample. At the sites where stubble was left after harvest (IRRI, PhilRice, BRIARC, Maros, and Lanrang), cutting height was measured from 20 hills to estimate the amount of crop residue left in the field. At the other sites, all above-ground biomass was removed after grain harvest.

Soils

Soils at the 11 sites represent Entisols, Inceptisols, Vertisols, Mollisols, and highly weathered soils (Jinxian, Shipai). Soil texture ranged from SiL to C (25–57% clay content). Clay mineral analysis by X-ray diffraction revealed that three soils (Shipai, Jinxian, Cuu Long) had predominantly 1:1 layer clay minerals (mostly kaolinite), whereas all other sites had a mixed composition of the clay fraction with dominating 2:1 layer minerals (micas, chlorite, smectite, vermiculite). Vermiculite was found at PhilRice, BRIARC, Lanrang, Qingpu and Pantnagar, whereas significant amounts of micas and chlorite occurred at Qingpu, Pantnagar, and Coimbatore. The IRRI soil is the only site with X-ray amorphous alumino-silicates as a major component of the clay fraction, occurring together with smectite [Bajwa, 1980].

Results and Discussion

Yield Response to Applied K

Grain yield of rice ranged from 3.6 to 7.8 and 3.8 to 8.1 t ha^{-1} in the NP and NPK treatments, respectively (Table 2). The average yield increase from K application was 8.5%, but K response differed significantly among sites (Table 3). At PhilRice, there was a 47% yield increase, and significant yield increases were also obtained at Coimbatore and Pantnagar (12–15%). All other sites showed no or only a slight K response of 3–5%. Agronomic K use efficiency ranged from 0 to 26 kg grain per kg fertilizer K applied. Since the beginning of the experiments, a significant K response has not been observed at IRRI [De Datta et al., 1988b], Lanrang, Maros or Qingpu, whereas the average long-term response at BRIARC, Jinxian, Shipai, and Pantnagar was somewhat larger than that in 1993. Only PhilRice showed a trend of increasing K response with time, which was also caused by increasing the fertilizer K rate from 50 kg ha^{-1} (1968–75) to 75 kg ha^{-1} (1976–91) and 100 kg ha^{-1} (since the 1992 wet season) to maintain soil K at adequate levels.

What are the reasons for the small K response at most sites in this study? One hypothesis is that high amounts of K were added from sources other than fertilizer. At IRRI, high K input from irrigation water (120–200 kg ha^{-1} per season) has resulted in a buildup in the extractable K[1] content in all treatments (1.5–1.8 cmol kg^{-1}), but none of the other sites had significant K inputs from irrigation or rainfall. Significant release of nonexchangeable K may have caused little or no K response on vermiculitic or micaceous soils such as BRIARC, Lanrang, and Qingpu. A third hypothesis raises the question of whether nutritional constraints may have limited K uptake and/or K response. A very small, nonsignificant K response was observed at the three sites which also had the lowest yields (Cuu Long, Shipai, Jinxian). Apparently, low N and P uptake has reduced K effects at those sites. At Jinxian, for example, a very low N/K ratio in the straw (0.7) indicated severe N deficiency. As shown at PhilRice (Table 3), significant response to K is only likely when N, P, and K supply is sufficient to support higher yield levels.

Potassium uptake and internal K use efficiency

Total K uptake in all treatments ranged from 23 to 257 kg ha^{-1} (Fig. 1). Mean K uptake was 95 kg ha^{-1} and mean grain yield was 4.9 t ha^{-1} across treatments and sites. By comparison, N uptake ranged from 20 to 200 kg ha^{-1} and P uptake from 4 to 34 kg ha^{-1} (data not shown). Potassium concentrations in grain were similar in all fertilizer treatments (0.27–0.30%) and did not vary much among sites, but differences in K nutrition status were clearly reflected by the K content in the straw, which was highest in the NK and NPK treatments (Table 4). We restrict our subsequent discussion to physiological efficiency (PE) or internal use efficiency defined as the amount of grain yield produced per kg nutrient taken up with the above ground plant biomass.

The slope of the relationship between grain yield and K uptake varied from 30-110 kg grain kg^{-1}K absorbed (Figure 1). Van Keulen [van Keulen, 1986] reported a range of 55–80 kg grain kg^{-1}K for rice, based on a small number of published reports. In irrigated rice, water is not a limiting growth factor and

[1] Throughout this paper, we use the term extractable K to include solution and readily exchangeable K as commonly extracted by 1 *N* NH_4 acetate.

Table 2. Partial net K balance in the Control, NP, and NPK treatments of LTFE at 10 sites, 1993 DS. All values are means of 3 replicate plots per treatment.

Site	Treatment	Extrac. K [1] cmol kg^{-1}	Grain yield[1] kg ha^{-1}	Fertilizer K input	Recycled K in stubble	Total K uptake [2]	Net K balance[3]
				——— kg K ha^{-1} ———			
IRRI[4]	Control	1.748a	4281b	0	50	92	-42
	NP	1.520b	7385a	0	163	253	-90
	NPK	1.660ab	7825a	40	147	257	-70
PhilRice	Control	0.207b	2594c	0	32	54	-22
	NP	0.137c	5464b	0	22	54	-32
	NPK	0.283a	8052a	100	114	209	5
BRIARC	Control	0.597b	3250b	0	26	51	-25
	NP	0.522b	7403a	0	45	120	-76
	NPK	0.707a	7009a	40	53	129	-36
Maros	Control	0.188a	3778b	0	43	92	-49
	NP	0.158b	5422a	0	44	107	-63
	NPK	0.177a	5572a	33	59	141	-49
Cuu Long	Control	0.251a	3567b	0	0	58	-58
	NP	0.212a	5280a	0	0	65	-65
	NPK	0.216a	5167a	25	0	74	-49
Shipai	Control	0.124a	3713a	0	0	59	-59
	NP	0.116a	3904a	0	0	60	-60
	NPK	0.124a	4001a	33	0	72	-39
Jinxian	Control	0.067b	2819b	0	0	31	-31
	NP	0.101a	3633a	0	0	38	-38
	NPK	0.114a	3830a	62	0	57	5
Qingpu	Control	0.206a	4377b	0	0	48	-48
	NP	0.196a	7804a	0	0	76	-76
	NPK	0.217a	7792a	33	0	102	-69
Pantnagar	Control	0.126b	2125c	0	0	36	-36
	NP	0.118b	5083b	0	0	74	-74
	NPK	0.192a	5685a	33	0	91	-58
Coimbatore	Control	0.750a	3269c	0	3	63	-60
	NP	0.708a	4840b	0	3	79	-76
	NPK	0.776a	5587a	41	6	123	-76
All sites [5]							
Control	Mean	0.279	3277	0	11	54	-43
	Stdev	0.221	631	0	16	22	20
N	Mean	0.260	4565	0	14	71	-57
	Stdev	0.217	1182	0	20	26	20
NP	Mean	0.251	5426	0	12	75	-63
	Stdev	0.200	1372	0	18	30	25
NK	Mean	0.326	4795	38	18	90	-34
	Stdev	0.245	1328	11	26	32	30
NPK	Mean	0.312	5855	44	25	111	-42
	Stdev	0.244	1362	24	40	49	42

[1] Means with common letters are not significantly different within sites by LSD (5%).
[2] Total K uptake = K grain + K straw.
[3] Partial net K balance = fertilizer K input - (K uptake-K recycled).
[4] Very high K input from irrigation (120–200 kg ha^{-1}). Actual net K balance is positive.
[5] Mean and standard deviation of 9 sites (without IRRI).

Table 3. Potassium response and K use efficiency in 10 long-term fertility experiments with irrigated rice in 1993.

Site	Variety	Yield increase due to K[1] NPK-NP		Internal K efficiency[2]	Agronomic K efficiency[3]	Δ Extractable K[4] NPK - Control
		kg ha^{-1}	%	$\frac{\text{kg grain}}{\text{kg K uptake}}$	$\frac{\Delta \text{kg grain}}{\text{kg K applied}}$	cmol kg^{-1}
IRRI	IR72	440	5	37 ± 7	9.9	-0.088
PhilRice	IR72	2588*	47	61 ± 27	26.0	0.077*
BRIARC	IR72	-394	0	59 ± 5	0.0	110*
Maros	IR74	150	3	42 ± 5	4.5	-0.011
Cuu Long	IR64	-113	0	68 ± 10	0.0	-0.035
Shipai	Guichaoxuan	97	3	57 ± 8	2.9	0.000
Jinxian	ER2106	197	5	76 ± 18	3.2	0.048*
Qingpu	Hanfeng	-12	0	89 ± 9	0.0	0.012
Pantnagar	Pant Dhan-4	602*	12	61 ± 5	18.3	0.066*
Coimbatore	CR1009	747*	15	56 ± 7	18.2	0.026

[1]Grain yield (GY) in NPK treatment minus grain yield in NP treatment.
[2]Internal K use efficiency = GY/total K uptake (all measured as kg ha^{-1}). Average ± standard deviation of all treatments.
[3]Agronomic K efficiency = (GY_{NPK}-GY_{NP})/fertilizer K applied (all measured as kg ha^{-1}).
[4]Extractable K in NPK treatment minus extractable K in the control, both measured in 1993 DS.
*Significant difference by LSD (5%).

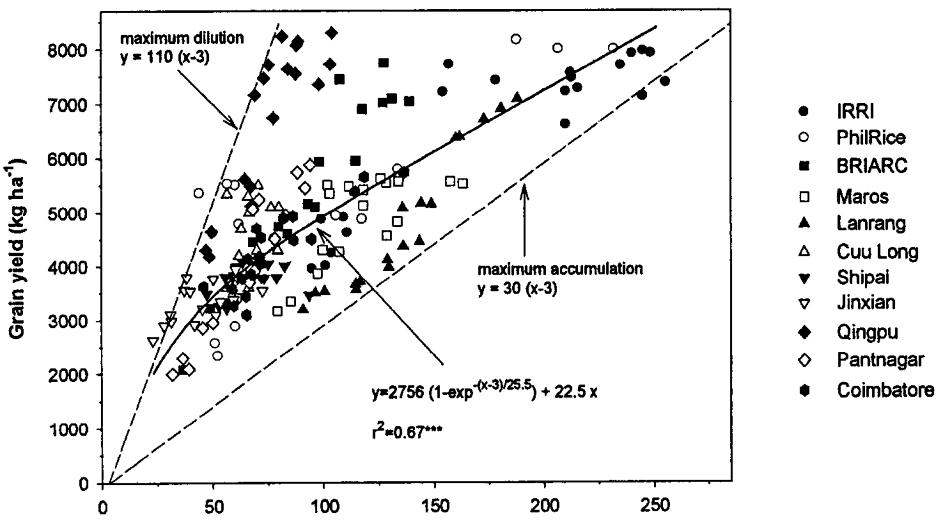

Figure 1. Relationship between grain yield and total K uptake at maturity in long-term fertility experiments with rice at 11 sites. Values shown are replicates of six fertilizer treatments at each site sampled in the 1993 dry season. Hand-drawn dashed lines show the possible envolope of maximum accumulation and maximum dilution of K in the rice plant. The solid line is the average function fitted to the data. In this equation, the (x-3) is a fixed constant describing the minimum K uptake (3 kg ha^{-1}) required to produce any grain yield. All other model parameters were significant at P<0.05. Because of rat damage, data of the NP treatment at Lanrang were excluded.

PE depends on the availability of other nutrients, harvest index (HI), nutrient losses by leaching from plant foliage, climatic factors, pests, and genotypic variation in internal efficiency mechanisms. Nutrient interactions seem to be major determinants of PE [Janssen et al., 1990]. With a limited K supply, there is maximum dilution of K in the plant, and uptake is not restricted by other growth factors such as N or P. The NP and N treatments of some sites with severe depletion of soil K reserves (Jinxian and PhilRice) were located close to this line (Figure 1) and, across all sites, the average PE of K was highest in NP treatments (68 kg grain kg^{-1} K uptake, Figure 2). When the supply of K is large and growth is not limited by uptake, there is

Table 4. Concentrations of K in grain and straw (% K) at maturity in different fertilizer treatments of LTFE with rice at 11 sites. Values shown are based on three replicates of each treatment at each site. The summary statistics shown are based on three replicates of all six fertilizer treatments at eight sites and five fertilizer treatments at three sites without a PK treatment (N=189 samples).

	Treatment	Mean	Minimum	25th percentile	75th percentile	Maximum
Grain	Control	0.30	0.20	0.23	0.35	0.45
	NP	0.30	0.21	0.26	0.33	0.45
	NK	0.27	0.19	0.23	0.30	0.35
	NPK	0.30	0.15	0.24	0.34	0.43
	All	0.29	0.15	0.25	0.33	0.45
Straw	Control	1.60	1.06	1.35	1.74	2.19
	NP	1.42	0.40	1.15	1.53	2.52
	NK	1.87	1.03	1.51	2.16	2.86
	NPK	1.81	1.24	1.45	1.98	2.90
	All	1.67	0.40	1.38	1.99	2.90

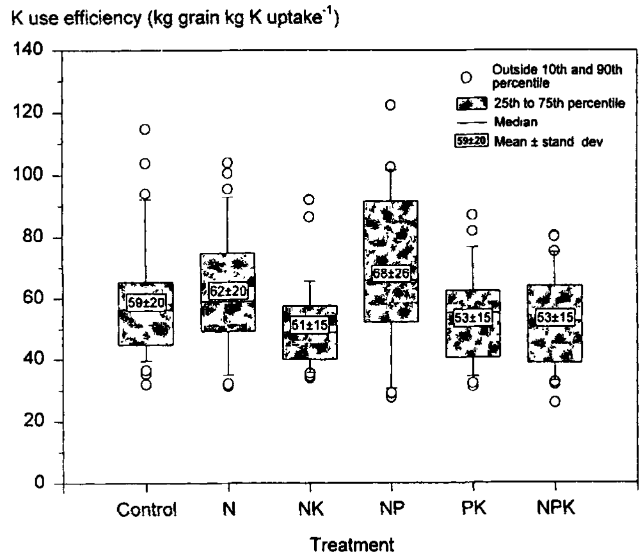

Figure 2. Internal K use efficiency in six fertilizer treatments of long-term fertility experiments at 11 sites in 1993. Boxplots are based on three replicates of each treatment at all sites.

maximum K accumulation in the plant [Janssen et al., 1990], as shown by the low PE of K in all treatments at IRRI (Table 3) and significantly lower PE (53 kg grain kg^{-1} K uptake) in NPK treatments than in minus K treatments (Figure 2).

To some extent the scatter in Figure 1 may be caused by variations in the grain/straw ratio, but the relationship between K harvest index and dry matter harvest index was poor (r^2=0.23*, Figure 3). Losses of K due to leaching from leaves or leaf senescence at the end of the grain filling period and partial replacement of K in the plant by other cations such as Na [van Keulen, 1986] are other factors that may affect PE. For example, most values from Qinqpu were very clustered near the minimum K dilution line (Figure 1), which may indicate K leaching from plant tissues by rainfall before the samples were collected. However, at most sites little rainfall occurred during the grain filling period and samples were generally taken close to physiological maturity to reduce leaf losses. Rice genotype differences in PE of K are uncertain.

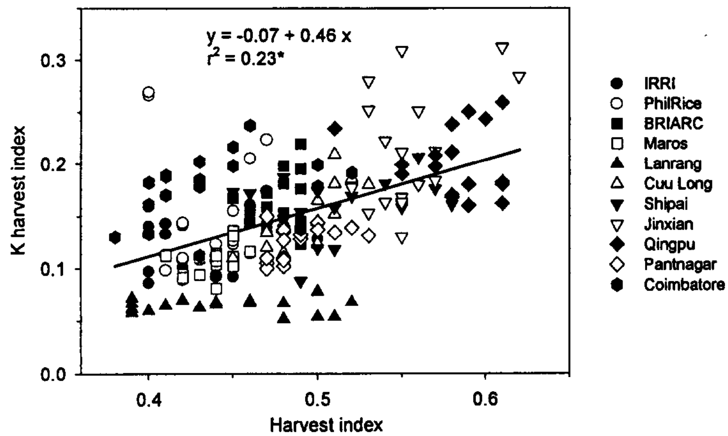

Figure 3. Relationship between potassium harvest index and harvest index in long-term fertility experiments with rice at 11 sites. Values shown are replicates of six fertilizer treatments at each site sampled in the 1993 dry season.

A model with an exponential component describing the nonlinear decrease in PE of K between 2 and 5 t ha^{-1} grain yield and a linear response component with an average slope of 22.5 kg K ha^{-1} t^{-1} grain for yields above 5 t ha^{-1} was fitted to the data from all sites and all treatments (Figure 1). A minimum uptake of 3 kg K ha^{-1} is required to produce any grain (x-3, Figure 1). This model suggests that at yields from 5 to 8 t ha^{-1}, the internal response to K is more or less constant, whereas at low yield levels source limitation occurs and internal K use efficiency is much higher. As estimated by this model, the average K uptake of rice in the yield range of 4–8 t ha^{-1} varied from 17 to 30 kg K t^{-1} grain. Yields of 5 and 8 t ha^{-1} would require total K uptake of 105 and 237 kg ha^{-1}, respectively.

The measure of PE used in our study is not an indicator of the true physiological K demand, because luxury consumption of K may occur as well. However, the relationship between grain yield and total K uptake (Figure 1) was based on a wide range of nutrient supply environments. As such they may cover the range expected to occur in farmers' fields and the model fitted may provide a general basis for estimating average rice K requirements. At present, we do not have enough data for rice yields beyond 8 t ha^{-1}, but reported uptake data for yields of 9–10 t ha^{-1} are in a range of 250–300 kg K ha^{-1}, compared with 160–220 kg N ha^{-1} [De Datta et al., 1985; Yoshida, 1981].

Partial Net K Balance

Estimating the complete K balance in an irrigated ricefield would require measurements of nutrient outputs due to crop removal, leaching, runoff, and seepage, and of nutrient inputs from fertilizer, recycled straw, irrigation water, rainfall, seepage, sedimentation, and capillary rise. In the small, bunded experimental plots at all 11 sites runoff, seepage, and sedimentation were of minor importance. Rainwater is usually low in K and only occasionally annual inputs may exceed 10 kg K ha^{-1} [Abedin et al., 1991; Handa, 1988]. At many sites in Asia, typical K concentrations in river or canal water range from 1 to 5 mg K L^{-1} [Kawaguchi et al., 1977; Handa, 1988], and, with an estimated net irrigation water supply of 700–1200 mm, the K input per rice crop would be in the range of 7–60 kg ha^{-1}. Water pumped up from deep aquifers contains somewhat more K [Handa, 1988], but of the sites investigated in our study only IRRI had significant K input from irrigation. In many cases, inputs of K from rainfall and irrigation seem to be comparable or even smaller than nutrient losses due to leaching and do not represent a net gain in nutrients [Abedin et al., 1991].

Therefore, we used a simplified approach for calculating the partial net K balance based on fertilizer input, aboveground uptake, and recycling with straw (Table 2). The average partial net K balance was highly negative in all NPK combinations tested (-34 to -63 kg ha^{-1} per crop cycle). Only at two sites, PhilRice and Jinxian, was the K balance in the NPK plots slightly positive, which reflected the higher K rates and greater amount of K recycled with the stubble at PhilRice and the low yield at Jinxian in 1993. Fertilizer K application at an average rate of 38–44 kg ha^{-1} in the NK and NPK treatments was not sufficient to match the K removal at most sites. Extractable K in the NPK treatments was not significantly different from values in the control plots at seven sites, indicating no accumulation of soil K from application of K fertilizer at the rates used.

These figures do not provide a complete picture of the K balance in irrigated rice. However, we conclude that in most intensively used rice-growing regions, K inputs do not match net K removal from the system, and that there is an alarming situation of continued K mining. Occurrence of response to K application is then a question of length of intensive cultivation, yield level, amount of NPK fertilizer applied, K-buffering capacity of the soil, and straw management. At many sites in Asia, the K rates applied by the farmers are even much lower than the rates used in the long-term experiments and, particularly on soils where straw is completely removed, K exhaustion may be even more rapid.

Extrapolated global conclusions

We used the data from the 11 sites to estimate the amounts of K cycling in intensive, irrigated rice ecosystems in Asia. We recognize the limitations of these extrapolations, but they provide a general overview of the magnitudes involved.

Irrigated rice accounts for 75% (363 million t in 1990) of the overall rice production in Asia and the present harvest area is 74 million ha, with an average yield level of 4.9 t ha^{-1}[IRRI, 1993]. Yields of irrigated rice in Asia must rise to 8.0 t ha^{-1} by the year 2025 with no change in the harvested area to meet a projected rice demand of 592 million t from irrigated systems [Cassman and Pingali, 1995]. In our study, the K content in the grain of modern rice varieties was less variable and 50% of all grain samples analyzed ranged from 0.25 and 0.33% K (Table 4). Thus, current annual K removal from irrigated ricefields with harvested grain is as large as 0.9–1.2 x 10^6 t. By 2025, this would increase to 1.5–2.0 x 10^6 t.

The actual net K removal from rice-based cropping systems is much greater due to increasing use of straw as forage, fuel, or for industrial purposes [Uexkuell, 1985]. Across all sites, about 80–85% of the K absorbed by rice remained in the vegetative parts at maturity and 50% of all straw samples analyzed contained between 14–20 kg K per ton of straw on a dry matter basis (Table 4). Based on the model shown in Figure 1, the total annual K accumulation by rice in irrigated rice systems of Asia is in the range of 5–9 million t (assuming 15–25 kg K t^{-1} grain across the most common yield levels in farmers' fields) and would have to increase to 9–15 million t by 2025. Clearly, this exceeds the present level of fertilizer K use on rice by a large margin and it may exceed the indigenous plant available soil K reserves as the major source of K supply.

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