MACRONUTRIENT TRANSFORMATIONS AND BUDGETING IN SOILS

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ABSTRACT

This review of selected papers discusses the transformations of N, P and K that affect the balance sheets of these nutrients for Indian soils, and it indicates the gaps in existing information that need to be filled before accurate nutrient budgets can be prepared. More detailed information is available for N than for P and K. In general, upland crops utilize fertilizer N more efficiently than wetland rice, where gaseous losses of N may be substantial. The appreciable proportion of fertilizer N that remains in the soil is of low availability to subsequent crops. For all three nutrients, more information is needed on losses by leaching and erosion. Additionally, for N, many more measurements are needed of gaseous N losses to provide a better understanding of the extent of losses. The currently available information indicates that, for many soils, nutrient inputs do not match removals. Development of accurate budgets requires nutrient-balance experiments at a greater number of benchmark sites.

The substantial increases in food production in India over the past 30 years are the result of modern agricultural technology. Fertilizers are one of the important components of this improved technology. Inputs of nutrients, particularly N and P, are a major factor in the realization of the greater production potential of improved crop genotypes (Randhawa and Tandon, 1982). Conversely, however, the use of improved genetic materials in intensive farming systems has greatly increased the need for inputs of plant nutrients compared to the requirements of the 'local' cultivars in less-intensive traditional agricultural systems. If the recent increases in crop productivity are to be maintained, nutrient budgeting must be considered : long-term sustainable agriculture depends on the maintenance of soil fertility.

In this paper, we focus on the effects of transformations of N, P and K on the balances of these nutrients in soils. Examples are given from both arable and wetland agriculture. Nutrient balances are important for several reasons. They provide information on the amounts of nutrients lost in crop production systems ; this information provides the basis for formulating budgets and fertilizer strategies to maintain soil fertility. Additionally, budgets assist in devising strategies for reducing pollution.

Nutrient budgets can be difficult to construct because of the interplay of different physical, chemical, and microbiological transformations. Nutrient budgeting is even more difficult in wetland soils, because of the presence of both oxidized and reduced layers, which together greatly affect especially N transformations, loss and availability to crops.

We will discuss the transformations that affect nutrient budgets in soils rather than discussing the nutrient transformations in isolation. We mention, at this stage, that there is a considerable lack of information on nutrient budgets in Indian soils. Nutrient budgeting for nitrogen has become more feasible with the increasing use of ^{15}N labelled fertilizers in N balance studies. Greater emphasis will therefore be placed on N budgets, partly because of the better information available and partly because of importance of nitrogen in crop production.

Nutrient transformations including those of N, P and K were discussed earlier by Goswami and Sahrawat (1982). For N transformations in arable and wetland soils, the reader is referred to Stevenson (1982), Indian Society of Soil Science (1984) and DeDatta and Patrick (1986).

NITROGEN

Nitrogen is a key element for crop production in India : cereal crops respond to N application on almost all soil types. The efficient use of fertilizer-N for crop production, however, depends on the several transformations that the fertilizer-N may undergo.

The important physical, chemical, and biological processes that affect N balance sheets are briefly discussed below. Subsequently, appropriate examples of balance sheets are given for upland and wetland soils.

Physical and chemical processes

- o Nitrogen movement—leaching and runoff
- o Ammonium fixation by soil clay minerals and amorphous materials
- o Ammonia volatilization

Biological processes

- Dinitrogen fixation
- Mineralization and immobilization
- Nitrification and denitrification
- Urea hydrolysis

The current state of knowledge of these different processes based on recent literature review (Goswami and Sahrawat, 1982 ; Stevenson, 1982 ; Indian Society of Soil Science, 1984 ; DeDatta and Patrick, 1986) is given below.

Movement of nitrogen : In arable soils, only nitrate is leached to any extent in percolating water. In wetland rice soils, however, even ammonium may be leached because the prevailing reduced conditions may release cations that displace ammonium from exchange surfaces, although such movement of ammonium will be appreciable only in soils with a low cation exchange capacity. Appreciable amounts of N may be lost by soil erosion and in runoff. Nitrogen leaching is an important factor influencing N budgets in coarse-textured soils under poor water management.

Ammonium fixation : Appreciable amounts of N are sometimes fixed by 1 : 2 layer lattice minerals. Such fixation can significantly influence N cycling and N balance in arable and wetland soils by preventing ammonium from participating in other transformations.

Release of non-exchangeable (or fixed) ammonium is slower in upland soils than in submerged soils.

Ammonia volatilization : This is an important loss mechanism in some calcareous and alkaline coarse-textured soils, especially when urea and ammonium fertilizers are applied to the soil surface. In wetland rice soils, high flood-water pH may greatly increase ammonia volatilization.

Biological nitrogen fixation : Estimates indicate that the amounts of N fixed in wetland rice systems vary widely, depending on the crops and other soil-crop-climate factors. The inclusion of legumes in these systems, either as sequential crops or as intercrops, provides sufficient additional N to reduce fertilizer-N requirements.

Mineralization and immobilization : Release of mineral N in soils is the net result of mineralization and immobilization reactions that may operate simultaneously though in opposite directions. Immobilization of mineral N can be a useful process for temporarily holding N from loss by leaching, dinitrification, or ammonia volatilization. Wetland rice soils have a lower N factor (additional N immobilized per unit weight of organic residues) for decomposition of organic matter, as compared to the upland soils, consequently the net release of mineral N is higher in submerged soils than arable soils.

The dynamic equilibrium that exists between mineral N and organic N, due to simultaneous degradation and synthesis of organic compounds in soils, is best studied with ^{15}N.

Nitrification : The conversion of the relatively immobile ammonium-N to nitrate-N is a key process affecting N balances, especially in wetland rice soils. In submerged soils, nitrate is liable to losses by leaching and denitrification : the presence of the oxidized and reduced soil layers in close proximity is an ideal system for causing loss by nitrification-denitrification. In coarse-textured soils, with high percolation rates, leaching of nitrate can be an important loss mechanism.

Nitrification inhibitors affect N cycling in soils because they affect distribution of N in the different pools : they can stimulate ammonium fixation, N immobilization, and ammonia volatilization (Sahrawat, 1988).

Urea hydrolysis : Urea hydrolysis in soils creates alkalinity, which promotes ammonia volatilization ; its further sustenance would depend on the sources of alkalinity in the soil or the soil-flood water system. In coarse-textured soils of high pH, rapid urea hydrolysis can cause substantial loss of N through ammonia volatilization of the surface applied urea.

Nitrogen budgets in soils. The N-balance approach outlined by Legg and Meisinger (1982) is used as a model to develop N budgets for Indian soils. In this approach, the N balance in a crop production system is simply represented as :

$$\text{N input} - \text{N output} \pm \Delta\text{N soil} = 0$$

N input = (N added through fertilizers, composts, residues and wastes) + (N in irrigation water and precipitation) + (biologically — fixed N_2)

N output = (N in harvested produce) + (N lost by leaching, ammonia volatilization, denitrification, runoff, soil erosion) + (change in soil N, ΔN soil)

Ideally, all of the input and output terms should be measured but this is not normally possible : thus, it is usually not possible to construct accurate N balances of soils. The use of ^{15}N labelled fertilizers has increased the accuracy of some N-balance terms, especially total losses and fertilizer-N removed by a crop. In the alternative (and older) approach, the changes in the total soil N are measured after a period of cropping, as well as the input in fertilizers and output in crop offtake; labelled-N is not used. It is usually assumed that there is little loss of N.

Examples are given for each of these approaches. Most of the Indian studies quoted were small-scale experiments carried out for one or more years.

Soil N balances : In a two-year study, Rao and Sharma (1978) determined the effects of six cropping sequences on N and P balances in a tarai soil (sandy loam, pH 7.0, 0.936% organic C). They found that total N in the soil (0-20 cm depth) at the end of 2 years decreased by 53 kg N/ha in a maize-wheat sequence, but increased under other crop sequences especially those involving legumes. Some results from this study are presented in Table 1. Although no statistical error terms were given, it is apparent that legumes in these rotations improved the total N content of the soil.

Table 1. Balance sheet of total N (kg N ha^{-1}) as influenced by different cropping sequences for 2 years

Cropping sequence	*Total N added*	*Total N removed*	*Initial soil N level*	*Final soil N level*	*Net gain or loss*
Maize-wheat	405	281	1986	1933	- 53
Soybean-wheat	281	465	1986	2000	+14
Maize-wheat-greengram	443	488	1986	2045	+59
Maize-potato-wheat	555	440	1986	1993	+ 7
Maize-Indian rape-wheat	495	398	1986	2010	+24
Maize-potato-greengram	413	424	1986	2067	+81

Source : Rao and Sharma (1978)

In another study, involving rice-based cropping systems, Sadanandan and Mahapatra (1973 a) constructed a N balance sheet from an experiment carried out for 2 years on a sandy loam soil. All treatments caused a loss of soil N ; the decrease was greatest in a maize-rice cropping pattern, and least in groundnut-jute-rice and the rice-jute-rice rotations. Inclusion of jute in the crop rotations tended to decrease the net loss of N. These results show that the soil N content decreased under a high cropping intensity unless substantial additions of nitrogen were made.

More and Ghonsikar (1984) evaluated the effects of two cropping sequences (sorghum-wheat and green gram-wheat) on N-use efficiency and soil N contents on a Vertisol (pH 8.0, 0.63% organic C). The sorghum-wheat sequence depleted the soil N, and the depletion was greater at the lower rates of N (50, 75 and 100 kg

N/ha) (Table 2). The application of 150 and 100 kg N/ha to wheat grown after greengram increased the soil N content (Table 3). Apparent recovery of N by wheat was similar in the two cropping sequences, and it decreased with an increased rate of K (Table 2 and 3).

Table 2. Effect of fertilizer N rates on the balance sheet of total soil N and apparent recovery of N for wheat crop in a sorghum-wheat cropping sequence

Nitrogen added	*Nitrogen removed by crop*	*Initial soil N level (before wheat)*	*Final soil N level*	*Net N gain or loss*	*Apparent recovery in wheat of added N (%)*
		kg N ha^{-1}			
0	23.2	1342	1295	—47	—
50	56.2	1342	1300	—42	66.0
75	60.6	1342	1320	−22	52.4
100	69.3	1342	1320	−22	46.3
125	80.2	1342	1338	— 4	45.6
150	83.1	1342	1348	+ 6	39.9

Source : More and Ghonsikar (1984)

Table 3. Effect of green gram on balance sheet of total soil N and apparent recovery of fertilizer N for wheat crop in a green gram-wheat cropping sequence

Nitrogen added	*Nitrogen removed by crop*	*Initial soil N level (before wheat)*	*Final soil N level*	*Net N gain or loss*	*Apparent recovery in wheat of added N (%)*
		kg N ha^{-1}			
0	24.6	1331	1298	33	—
50	56.9	1331	1314	−77	64.6
75	68.8	1331	1331	0	58.9
100	79.6	1331	1342	+11	55.0
125	82.4	1331	1357	+36	46.2
150	84.0	1331	1376	+46	39.6

Source : More and Ghonsikar (1984)

^{15}N-Balance-studies. In one of the earlier experiments using ^{15}N labelled fertilizers, Datta *et al.* (1971) made an N balance study on submerged rice in pots in a greenhouse. They directly measured N loss by ammonia volatilization and denitrification in addition to measuring the recovery of N in the rice plants. The

volatile loss of ammonia was negligible. The loss of N by denitrification from ammonium sulfate, nitrophosphate with high water solubility, and nitrophosphate with low water solubility was 24.1, 30.2 and 53.7%, respectively. The N balance sheet is summarized in Table 4. Most of the N lost by denitrification was in the form of N_2 gas, which is in accord with the recent concepts : flooded soil conditions promote synthesis of the nitrous oxide reductase enzyme, which converts N_2O produced by denitrification to N_2 (for review see Sarhawat and Keeney, 1986).

Table 4. Nitrogen balance sheet of fertilizer N in pots for submerged rice crop

Treatment[1]	*Dry matter yield (grain+straw) g pot*^{1}	*Fertilizer N (%)*			*Tatal*	*Fertilizer N (%) evolved*		
		Crop	*Soil*	*Leachates*		NH_3	NOx	N_2
AS+SP	44.17	59.8	2.2	0.4	75.0	Trace	0.02	24.1
NP (LW)	36.33	36.6	1.6	1.5	45.4	Trace	0.03	53.7
NP (HW)	43.40	57.6	2.0	1.3	69.3	Trace	0.04	30.2

1. AS+SP, Ammonium sulfate+single superphosphate
   NP (LW), Nitrophosphate with low water solubility
   NP (HW), Nitrophosphate with high water solubility

Fertilizers were added to supply 136 kg P_2O_5, and 68 kg K_2O ha^{-1}

Source : Datta *et al* (1971)

Although the recovery of ^{15}N by rice under greenhouse conditions in this experiment was relatively high, the literature generally indicates that wetland rice uses N less efficiently (30-40%) than the arable crops (50-60%) (Craswell and Vlek, 1979).

Oza and Subbiah (1980) studied the fate of ^{15}N labelled fertilizer in a multiple cropping system, (wheat-green gram-maize) on an alluvial soil (pH 8.6, 0.67% organic C). About 20 to 30% of the N applied (as urea at 50, 100 and 150 kg N/ha) was utilized by wheat, the first crop in the sequence. Although 38 to 43% of fertilizer-N remained in the soil after wheat crop, very little was utilized by succeeding greengram and maize crops. These results agree with those of other workers (Prasad and Subbiah, 1982 ; Goswami *et al.*, 1984 ; Moraghan *et al.*, 1984 a, b). For example, in a maize-wheat-moong cropping system rotation on an alluvial soil, Prasad and Subbiah (1982) reported that only 2 to 4% of the labelled N applied to the maize was taken up by the succeeding wheat crop, and less than 1.5% by the moong crop (Table 5).

Moraghan *et al.* (1984 a, b) made field studies on Vertisols and Alfisols at ICRISAT Center in two successive rainy seasons to determine the fate of ^{15}N

Table 5. Utilization of fertilizer ^{15}N and N balance in a maize-wheat-mungbean cropping sequence

N recoverd (%) in	1977-88	1978-79	1979-80
Maize	20.9	24.5	32.3
Wheat	2.3	4.0	—
Mungbean	0.6	1.4	—
Soil (0-180 cm depth)	55.3	64.9	64.8

Source : Prasad and Subbiah (1982)

labelled fertilizers applied to rainfed sorghum. In the Vertisol, the recovery of applied N (74 kg N/ha) in the soil-plant system after the sorghum crop was 94, 72 and 74%, respectively, for fertilizer applied by split-banding, broadcast onto the soil surface and broadcast followed by incorporation into the soil. Substantial quantities (39 to 45%) of the added-N remained in the soil after harvest of the crop. Recovery of added urea-N in the above-ground crop components was similar in both seasons ; it ranged from 48.0 to 55.7%, depending on the method of N application. Typical data from this study are given in Table 6. The residual soil N derived

Table 6 Grain yield, N uptake. and N recovery for indicated methods of applying urea (74 kg N ha^{-1}) to sorghum on a Vertisol, ICRISAT Center, rainy season 1981

	Surface broadcast	*Broadcast incorporated*	*Split band*	*SE*
Grain yield (kg ha^{-1})	4260	4110	5220	±225
N uptake (kg ha^{-1})				
Total	62.1	60.2	84.4	±3.84
From fertilizer[1]	22.3	21.3	39.6	±1.09
From soil	39.8	38.9	44.8	
Recovery of fertilizer-N (%)				
Apparent (plant)[2]	31.8	30.0	61.9	±6.00
^{15}N				
- in plant	31.0	29.6	55.0	±1.55
—in soil	41.8	45.2	38.6	±2.69
—plant+soil	72.8	74.8	93.6	±2.41
Residual fertilizer-N in soil (kg ha^{-1})	31.1	32.5	27.8	—

1. Calculated from ^{15}N content of plant 2. From total N content of plant

Source : Moraghan *et al.* (1984 a)

from the fertilizer applied in rainy season was not taken up to any extent by a safflower crop (1.5 to 4.2%) in the following postrainy season or a sorghum crop (1.3 to 1.7%) in the next rainy season.

For the Alfisol, the recovery of ^{15}N labelled urea in the above ground parts ranged from 46.7 to 63.6% in 1981 (rainfall above the average of 750 mm) and from 54.4 to 66.9% in 1980 (rainfall near average). A ^{15}N balance sheet of the plant soil (0-90 cm depth) system in 1981 showed that the unaccounted-for fertilizer N ranged from 5.1 to 20.6%. The 1981 rainy season results are summarized in Table 7.

The results of this research at ICRISAT show that fertilizer-N is efficiently utilized by a rainfed crop such as sorghum on Vertisols and Alfisols under assured rainfall. Yields of over 5000 and even 6000 kg/ha of sorghum were obtained ; losses of fertilizer-N could be small, particularly in the Alfisols (Tables 6 and 7).

Table 7. Grain yield, N uptake, and N recovery for indicated methods of applying urea (80 kg N ha^{-1}) to sorghum on an Alfisol, ICRISAT Center, rainy season 1981

	Surface broadcast	*Broadcast incorporated*	*Band split*	*Band all basal*	*USG*[1] *point*	*SE*
Grain yield (kg ha^{-1})	5450	4570	6040	5330	5190	±320
N uptake (kg ha^{-1})						
Total	95.4	83.6	102.5	92.8	94.7	±6.23
From fertilizer[2]	40.7	39.6	50.0	45.9	46.8	±1.76
From soil	54.7	44.0	52.5	46.9	47.9	
Recovery of fertilizer-N (%)						
Apparent (plant)[3]	79.4	64.6	88.2	76.1	78.5	±8.80
^{15}N						
—in plant	50.9	49.5	62.5	57.4	58.5	±1.96
– in soil	36.5	33.7	27.1	31.4	33.3	±2.56
– plant+soil	87.4	83.2	89.6	88.8	91.8	±2.99
Residual fertilizer-N in soil (kg ha^{-1})	28.5	27.0	21.6	25.1	26.1	

1. USG—Urea super granule appliad as 1 granule 2 plants^{-1}
2 Calculated from ^{15}N content of plant 3. From total N content of plant
Source : Moraghan *et al.* (1984 b)

In subsequent studies on the fate of different ^{15}N labelled fertilizers in a shallow black soil (Vertic Inceptisol) and a deep Vertisol, the recovery of ^{15}N fertilizer by sorghum on deep Vertisol under average rainfall was again high ; but, fertilizer-N recovered in the crop and soil was low (< 70%) on the shallow black soil under high rainfall (Table 8). Leaching of N was suspected to be the cause of lower N recovery.

Table 8. Recovery (%) of fertilizer-N applied in different carriers to sorghum CSH 6 on a Vertisol in 1982 and a Vertic Inceptisol in 1983, ICRISAT Center, rainy season

	Vertisol (1982)[1]			*Vertic Inceptisol*		
	Plant	*Soil*	*Total*	*Plant*	*Soil*	*Total*
Urea	56.2	35.0	91.2	36.3	34.6	70.9
Potassium nitrate	66.1	25.6	91.7	34.8	23.4	58.2
Nitro-phos[2]	60.6	32.5	93.1	29.7	40.5	70.2
USG[3,4]	57.2	26.9	84.1	—	—	—
Ammonium nitrate	55.0	31.8	86.6	—	—	—
SE	±3.2	±3.1	±3.0	±1.0	±2.0	±1.4

1. Rainfall during the crop season was 550 mm in 1982, and 910 mm in 1983
2. Ammonium-nitrate-phosphate (20-20-0)
3. Urea super granule (approximately 1g granule)
4. Recovery calculated from basal dose, others are average recovery from basal dose and top dress dose Source : ICRISAT Annual Report (1985)

Conclusions. This brief discussion clearly brings out that fertilizer N is relatively inefficiently used by wetland rice as compared to upland crops. For upland cereals such as sorghum, efficient use of N by crops can be achieved with good management with nearly 50% of the added N being utilized by the crop.

Limited studies with ^{15}N indicate that a large proportion of the added N remains in the soil after cropping, but the availability of this N to a subsequent crop is very low (< 5%). Further research is needed to understand the relationship between the nature of this residual N and its availability.

There is an obvious need for more N balance sheets under different cropping systems, especially those involving cereals and legumes in rotations or intercropping There is an urgent need to make direct measurements of gaseous loss of N, rather than assessing these by the lack of recovery of N (unaccounted-for-N) in ^{15}N recovery experiments. Data also need to be obtained on the components of the N balance equation that are not normally measured (e. g., loss in runoff and erosion ; and gains via rainfall and irrigation water) so that complete balance sheets can be constructed. A large body of N-balance data would permit development of N budgets for different regions of the country, and finally for the country as a whole. This would help in developing sound crop production strategies that aim to maintain soil fertility.

PHOSPHORUS

Transformations of P in upland and wetland soils have been extensively reviewed (Indian Society of Soil Science, 1979 ; Goswami and Sahrawat, 1982 ; Tandon, 1987). However, very few attempts have been made to construct balance sheets for P in soils (Kanwar *et al.*, 1982 ; Tandon, 1987), possibly because losses of P from soil appear to be small. Soluble P is rapidly converted into insoluble forms in soils, and leaching losses are small. Crop removal of added P is about 20 to 25% in a single cropping season (Tandon, 1987).

Phosphorus transformations in soils. Phosphorus transformations in soils are affected by fertilizers and soil and crop management practices. The soil factors that affect P transformations include pH, organic matter, $CaCO_3$, temperature, moisture regime, mineralogical makeup, amorphous and free sesquioxides, root exudates, and microbial population.

The following salient points can be made from the extensive literature on transformations of P in soils.

- After addition to soil, water soluble P disappears rapidly from the soil solution due to reaction with soil constituents. The reactions include sorption and formation of reaction products.
- Relatively insoluble sources of fertilizer-P (e. g., rock phosphate) become available to plants by releasing water soluble P, which is, however, subject to reactions with the soil constituents
- Specific P compounds have been identified in the reaction products. These include calcium aluminium phosphates, ammonium-taranakite, variscite (in acid soils), and struvite and brushite (in calcareous soils).
- A common, less specific way of chemically characterizing P in soil is to estimate the P associated with Al, Fe, and Ca, using the Chang and Jackson procedure (Chang and Jackson, 1957).
- While Fe- and Al-P are dominant forms of P in the profiles of mature and sub-mature soils, Ca-P is the most important fraction of inorganic P in immature soil profiles. Forms of P are affected by cropping systems, moisture regime, and rhizosphere effects of crops.

- Flooding of soils usually increases P availability because ferric P is reduced to ferrous P (main source of P for wetland rice), organic acids are produced (which enhance solubilization of P), and the soils tend to attain neutral pH.

- Phosphate adsorption and desorption are perhaps the most important processes governing P availability and removal. The relative sorption capacity of different clay minerals; e.g., kaolinite, illite, montmorillonite, gibbsite, and others etc. have been generally characterized (Indian Society of Soil Science, 1979), but the effective sorption by $CaCO_3$ is not well understood. P sorption has not been closely related to $CaCO_3$ content (Goswami and Sahrawat, 1982) perhaps the fineness of subdivision (or particle size) is the critical factor.

- Significant amounts of phosphate can be leached by flooding of a sodic soil during its reclamation. Apparently, highly soluble sodium phosphates formed by the reaction between Na_2CO_3 and native monocalcium phosphates move downwards with water. Movement of water is further facilitated by gypsum application.

Phosphorus budgets in soils. Phosphorus budgets are more simple to develop than N budgets. They involve addition of P through chemical fertilizers, manures, crop residues, and other wastes. We assume that there is very little loss of P from the soil, but P losses in runoff and soil erosion need quantifying. Additions through precipitation are assumed to be small. Thus, our present knowledge of P balances is incomplete.

Tandon (1987) has reviewed the extensive literature on the removal and addition of P in short- and long-term experiments involving several crops and cropping systems. The amount of P required by crops to produce 1 t of harvestable yield varies greatly for different crops and cropping systems and their intensity and crop production levels. For example, the amount of P absorbed per tonne of produce may be 1 kg for tubers, 5 kg for cereals, 6 kg for grain legumes, 10 kg for oilseed crops, and 17 kg for tea.

The amount of P removed by crops also varies with cultivars and soil type. However, there is always a degree of uncertainty about assessing P removal by crops over a wide range of soils. Further, because changes in total soil P are difficult to measure, researchers commonly use chemical extraction tests to indicate the changes in P status during an experiment. For example, Sadanandan and Mahapatra (1973b) determined the changes in total- and available-P on a sandy loam soil in a 2-year study involving 5 annual cropping patterns of potato-rice-rice, maize-rice-rice, groundnut-jute-rice, rice-jute-rice, and rice-rice. There was no detectable gain or loss of total P in any of the cropping patterns during both years. Available P, however, declined in all treatments. The maximum depletion was observed in maize-rice-rice, rice-jute-rice, and rice-rice cropping patterns.

Prasad *et al.* (1985), in a 4-year study, investigated the fertilizer-P requirement and P changes in an intensive annual cropping pattern involving wheat-greengram (or cowpea)—pearl millet on an alluvial soil (pH 8.4, 0.52% organic C). A total production of 9-10 t of wheat equivalents annually removed 30 kg P ha^{-1}. Productivity of the cropping system was increased with P applied up to 58.5 kg P ha^{-1} of which two-thirds was applied to wheat, and green gram or cowpea and pearl millet received the remainder. A positive P balance in available P was observed only when 26 kg P ha^{-1} or more was applied annually. With phosphate fertilization at 52 to 58.5 kg P ha^{-1} annually, about half of the amount was added to the soil available P pool. Without P application, a depletion of 15 kg P ha^{-1} yr^{-1} was observed. Some typical results from this study are summarized in Table 9.

Table 9. **Yield (wheat equivalents) and available P balance in soil under intensive annual cropping with wheat-greengram/cowpea-pearmillet (1971-75)**

Wheat equivalents	*P added*	*P removed*	*P balance in soil*
t ha^{-1}		*kg P ha^{-1} a^{-1}*	
5.8	0.0	14.9	−14.9
6.2	6.5	15.1	− 8.6
7.3	13.0	19.5	− 6.5
7.7	19.5	21.3	− 1.8
8.2	26.0	23.5	+ 2.5
8.9	39.0	27.9	+11.1
9.1	45.5	28.5	+17.0
9.3	52.0	27.3	+24.7
9.6	58.5	30.5	+28.0

The loam soil (pH 8.4) had initial extractable P (0.5 *M* $NaHCO_3$) of 4.4 µg P g^{-1} soil
Source : Prasad *et al.* (1985)

A survey of Indian literature indicates that the crop recovery of added P varies from 5 to 35% on a single crop bases with a mean of 15-20% (Tandon, 1987).

Tandon (1987) calculated a P balance sheet for Indian agriculture for the year 1983-84, based on the limited data available for inputs and outputs of P. For inputs, it was assumed that the fertilizers-P efficiency (uptake by plants) was 20% for chemical fertilizers and 10% for farm yard manure (FYM) and composts. It was also assumed that 5% of total P was recycled to the soil through crop residues (roots, leaf fall, etc.). For the output terms, 95% of the total P uptake by crops was assumed as the net P removal. No corrections were made for removal of P in grazing or soil erosion, because of lack of data. The balance sheet (Table 10) suggests that Indian agriculture depends heavily on exploiting soil-P reserves because P additions considerably exceed removals. These results are in general agreement with the P balance sheet presented by Kanwar *et al.* (1982).

Table 10. An illustration of a P balance sheet in Indian agriculture using 1983-84 data

	Gross	*Net*	*Remarks*
	$10^3 t$ P_2O_5		
Input			
Fertilizers, 20% efficiency	1730	346	Gross is actual consumption and net is 20% of 1730
FYM, 10% efficiency	750	75	Gross is 50% of total dung available
Composts, 10% efficiency	1140	114	Gross is total production
Crop residues, 10% efficiency	130	13	Gross is 5% of total uptake
Total for input	3750	548	
Output			
Crop uptake, 95% net removal	2600	2470	
Grazing	no estimates available		
Soil erosion	not considered		
Total for output	2600	2470	
Balance	+1150	1922	Excluding erosion and grazing

Source : Tandon (1987)

Conclusions. There is insufficient data on several aspects pertaining to input and output terms of P balance sheets. There is an urgent need to generate data for different regions particularly with regard to the amounts of P lost in runoff and erosion, and fertilizer (and organic manure) use efficiency for P as affected by soil types and cropping systems.

POTASSIUM

Several reviews are available on different aspects of K in soils and plants (see Indian Society of Soil Science, 1976, Sekhon and Singh 1982, Goswami and Sahrawat 1982, Nambiar and Ghosh 1987).

Potassium transformations in soils In soil K exists in three main forms : solution, exchangeable, and non-exchangeable (reserve) K. These three forms are in a dynamic equilibrium; knowledge of the equilibria is central to an understanding of the availability of K to crops. The important transformations that K undergoes in soils are leaching, and fixation by and release from clay minerals. Some important points emerging from the recent literature are summarized below.

1. Fixation and release. Both are affected by pH, cation exchange capacity (CEC), nature of cations, nature of clay minerals, and moisture regime. Potassium fixation increases with the increase in pH, CEC, and moisture regime. Among the different types of soils, alluvial soils and Vertisols (with illite and motmorillonite as the dominant clay minerals) have higher K fixing capacity than Alfisols and laterites (dominant in 1:1 clay minerals) (Sekhon and Singh, 1982).

2. Leaching. Leaching of K in soils is affected by clay content, clay mineralogy of the soil, moisture regime, and rooting pattern of crops. Leaching of K beyond the root zone has been found to be negligible in soils with 2:1 clay minerals, but can be appreciable in soils with 1:1 clay minerals.

Potassium budgets in soils. Nambiar and Ghosh (1987) summarized the results of long-term experiments carried out over 12 years (1971-83) under different agro-climatic and soil conditions in India. Their results (Table 11) showed that, under intensive cropping, crop removal of K exceeded the quantity added even when fertilizer K added was 150% of the optimum recommended rate. The greatest depletion of soil reserves occured when N and P were added but K was not.

Again, as in the case of N and P, K budgets presented are rough estimates in the absence of data on loss of K by leaching and soil erosion, and the contribution from precipitation.

In a long-term K experiment using a rotation of two improved intercrops on an Alfisol at ICRISAT Center, the first 4-year cycle of the experiment showed only that all crops responded marginally to K application. Substantial amounts of K were removed from the soil over the 4-year period (55 kg ha^{-1} year ^{1} with no N added), and most of this K came from the soil reserves. The changes in exchangeable K were small (ICRISAT, 1984). The soil has very large K reserves (approximately 80,000 kg K/ha in the 0-30 cm horizon) and K was released from the reserves at fairly rapid rate. The result showed that input of about 70-75 kg K ha^{-1} yr^{-1} is required to maintain the initial K status. Clearly, even though the marginal K deficiency may not become more severe because of rapid release of nonexchangeable K, the improved cropping systems are exploiting the soil K reserves : eventually, maintenance inputs of K will be required.

Conclusion. Further research is required to allow accurate assessment of the role of K in Indian dryland agriculture. The poor predictability of K response by

Table 11. Potassium balance in soils under different intensive cropping systems, 1971-83

Center	*Soil*	*Cropping systems*	*Total no. of crops*	*K balance, kg K ha^{-1}*				
				K added (100% NPK)	*K removed by crops*	*Balance*	*Mean annual balance*	
							100% NPK	*100 NP*
Ludhiana	Ustochrept	Maize-wheat-cowpea (fodder)	35	1242	2788	—1546	—55	—191
Jabalpur	Pellustert	Soybean-wheat-maize (fodder)	23	545	3102	—2557	—362	—401
Hyderabad	Tropaquept	Rice-rice	19	471	1668	—1197	—126	—179
Bhubaneswar	Tropauept	Rice-rice	23	1141	2028	- 887	—77	—111
Paiampur	Hapludalf	Maize-wheat	21	1153	1223	- 70	- 31	—91
Pantnagar	Hapludoll	Rice-wheat-cowpea (fodder)	24	633	2737	—2104	- 257	- 322

100% optimal NPK rates based on initial soil tests and local recommendations

Source : Nambiar and Ghosh (1987)

standard soil tests is one problem; related to this is the apparently rapid release of non-exchangeable K in some soils. Because changes in non-exchangeable K are difficult to measure directly, K balance can only be determined by carefully conducted long-term experiments. More of these are needed at carefully selected benchmark sites, to allow development of more accurate budgets.

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