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Invited Article

Nutrient Management in Indian Agriculture with Special Reference to Nutrient Mining — A Relook

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The necessity of increasing food production to meet the demand of the ever-increasing population in India hardly requires any over-emphasis. Estimates suggest that at the current level of production (263 million tonne, Mt), an additional 5 Mt food grain has to be added each year to the national food basket for the next decade or so to feed the increasing population. The total area under cultivation remained more or less constant (at 140-142 Mha) over the past several decades, and there are indications that the agricultural lands are gradually being diverted to accommodate increased urbanization and industrialization. It is unlikely that sizable additional area will be brought in under cultivation in the foreseeable future. Therefore, there is no other viable option than increasing crop productivity per unit area, to meet the future production goals.

Maintenance of native soil fertility in the intensively cultivated regions of the country is one of the preconditions of maintaining and improving the current crop yield levels. Intensive cropping systems remove substantial quantities of plant nutrients from soil during continued agricultural production round the year. The basic principle of maintaining the fertility status of a soil under high intensity crop production systems is to annually replenish those nutrients that are removed from the field. Indeed this becomes more relevant in the absence of the measures for adequate replenishment of the depleted nutrient pools through the removal of crop residues from agricultural fields (Sanyal 2014). One would use the term "*Nutrient Mining*" when the quantity of soil nutrients removed by a crop from an agricultural field exceeds the amount of the nutrient that is recycled back and/or replenished to the field. Nutrient mining causes a decline in the native soil fertility and may seriously jeopardize future food security of the country. Unfortunately, the concern for nutrient mining in Indian soils is largely limited to the scientific community and has not been integrated adequately with the crop production practices.

Nutrients More Prone to Mining

The nutrient mining issues concern the nutrients that are less mobile in soils and have higher potential of staying in the soil. For example, nitrogen (N) is highly mobile in the soil and has the highest probability, among the major nutrients, to be lost from the soil system through volatilization and leaching, among others. The Indian soils, being in the sub-tropical region coupled with the preponderance of tillage practices, are rarely sufficient in N. Nitrogen is generally applied in adequate quantities to the crops, and "nitrogen mining" is not frequently discussed as crop production relies more on adequate external application through fertilizer/manure sources rather than on the native soil reserve of N. The input-output balance calculations for N, at the regional or the national scale, generally show positive balance in soils (Katyal 2001).

Phosphorus (P) and potassium (K), on the other hand, have lower potential for loss from the soil than N. Except erosion (P) and leaching (K), the extent of loss by other means is negligible for these two nutrients. Phosphorus, by virtue of fixation through the pH-dependent processes, is relatively immobile in soils and excess application of P through fertilizer may lead to P build-up in soils. Immediate availability of such fixed P to the plant is limited, but nonetheless it provides a source of slow supply of P in the long-term. Some assessments, based on total inputs and outputs, have shown a positive balance of P in Indian soils (Tandon 2007). However, recently published papers on P response across a range of Indian

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soils showed significant yield loss of cereals when P fertilizers are not applied to the crops (Singh *et al*. 2014a). Phosphorus application to meet in-season demand of crops may be needed even in soils where a large amount of P resides in fixed forms of different degrees of solubility (Sanyal and De Datta 1991). This is due to the fact that the release from the fixed pool of P may not meet the crop requirement at physiologically high P demand stages of the crop. The latter may lead to a situation wherein P balance calculations may turn out to be positive, but nevertheless the crop may respond significantly to the external application of P.

Potassium, being a component of soil minerals, mica and feldspar, is unique among the three major nutrients. In contrast to N and P, presence of mica and feldspar in soils provide an abundant *in-situ* source of this nutrient. Besides, K gets absorbed in the negatively charged interlayer space of soil clays, a process that prevents its loss from the soil and still keeps the nutrient in available form for plant uptake. However, on the issue of nutrient mining, K is probably the most pertinent nutrient that has the potential of significantly affecting agricultural production in the country. Historically low application rates of K in crops have led to over-dependence on the native soil reserve of K (Sarkar *et al*. 2014). The current estimates and increasing response to external application of K in crops suggests that we might have reached a point where K mining from soils should be addressed in a pro-active manner for maintaining the soil fertility status of India.

The cases of secondary and micronutrients are quite similar to K. Mostly they have geogenic sources in the soil, like K, while other anthropogenic activities can also enrich the soil native reserves. Historically, applications of secondary and micronutrients in crops are limited in India. There is increasing awareness at the policy and the grass-root level about the rising deficiency of sulphur (S), zinc (Zn) and boron (B) in Indian soils. But it appears that despite the lessons learnt from other nutrients, we are apparently waiting for other secondary and micronutrients to show up in the "highly deficient" category before we act. The information on crop nutrient balances, an indicator of nutrient mining, for secondary and micronutrients is very sketchy, to say the least. The information on - what is the soil reserve of these nutrients and where are the deficient areas, how much of these nutrients do we actually need to meet crop demand at the country-scale and how much are we applying to the soil - is available at a very rough scale. As the crop requirements for these nutrients are low, at ppm or few kg level, we rarely give enough importance to their mining from soils. This is *notwithstanding* the fact that the deficiency of these nutrients is taking a major toll on the food and economic security of the country in terms of the yield and economic losses due to unachieved yield goals (Shukla and Behera 2012).

Unfortunately, we have very little provision to track the soil nutrient availability on a temporal basis in India (Singh *et al.* 2012). The attempt to develop fertility maps is fragmented, and is fraught with the inherent weakness of developing extrapolated maps from low number of soil sample analysis data. Such maps rarely give a reliable picture of actual native nutrient reserves. This is particularly true for a country like India where small-holder systems of farming renders the soils with high spatial and temporal variability in nutrient availability. In the absence of a national soil fertility database or repository, we do not have any option to temporally track the changes in soil fertility levels in Indian soils. In other words, our sense of a comprehensive picture in terms of nutrient availability in Indian soils is a synthesis of fragmented scientific information rather than the one based on fine-scale spatially distributed scientific data that is accessible and available for critical analysis and interpretation. As a consequence, the extent of P build-up in soils or native reserve of K in soils is often overestimated.

Nutrient Mining – Balancing "additions" and "removals"

The biggest entry on the plus side of the nutrient balance equation is the native soil reserve of a nutrient at any given point of time. The nutrients may come from several sources including parent material, irrigation water, crop residues, or as by-products of natural events. The other two significant entries on the plus side are external application of manures and fertilizer. Although all the additions are dynamic in nature, the proportion of nutrient addition through irrigation water, crop residue, *etc*., to the total reserve of a nutrient in a soil is low. This is particularly true for nutrients like K. In common banking parlance, this could be considered as a "fixed deposit" that is saved for posterity. Manures and fertilizer application to soil, on the other hand, could be considered as "regular deposit" that is immediately available for use by the plants. Maintenance of soil fertility requires that we use the "regular" deposits for crop production without significantly depleting the "fixed" deposits.

The largest minus in the nutrient balance equation is the crop uptake and removal. Crop uptake and removal becomes synonymous when crop residues are largely removed from the fields along with the harvest of the economic products. This is particularly true for most field crops grown in India as there are a large number of competitive uses of crop residues. The uptake of nutrients per unit of economic produce is unique for each crop. For example, rice requires about 14.6 kg N, 2.7 kg P and 15.9 kg K to produce 1000 kg grain (Buresh *et al*. 2010), while 22.8 kg N, 4.4 kg P and 19.0 kg K are required by wheat to produce 1000 kg grain (Chuan *et al*. 2013). Based on the achieved yields, crops remove nutrients from the soil and that constitutes the largest depleting factor of soil nutrients. Besides crop removal, there are other avenues of losses of nutrients from the soil such as volatilization, leaching, erosion, run-off, *etc*. These losses could contribute significantly to the negative side of the nutrient balance equation under specific crop growing conditions. Volatilization of surface applied urea in calcareous soils or leaching of K in coarse textured soils are examples of typical growing environment-induced losses of nutrients from soil that could be easily rectified by modifying the management decisions.

Such nutrient input-output information could be used to develop nutrient balance information at local, regional or national scale. This may help in fertilizer application decision at the field scale to fertilizer import and distribution policies at the regional or the national scale. Recently, Dutta *et al*. (2013) estimated the K budget for different States of India by analyzing the amount of K-fertilizer received by the agricultural soils through inorganic and organic sources, the removal of K by different agricultural crops, and determined the K accumulation or removal from the soil. The study highlighted that the K balance (*i.e*. difference between K applied through fertilizer as well as manure and the removal of K by the major crops) was negative for most of the states across India in the year 2007. These negative values increased in the year 2011 probably due to lesser fertilizer application and/ or higher crop production. The K balance data highlights negative values that indicate depletion of K from soil and therefore mining of K after harvesting. Such depletion may not be immediately apparent through assessment of the plant-available K in soils as it may be made up by slow replenishment from the non-exchangeable pool of soil K that is usually not measured during soil testing. They suggested that such unnoticed depletion of K from the soil might seriously deplete the K fertility status of the soil that will require much higher investment in future to restore the fertility levels. The temporal soil K budget maps (Dutta *et al*. 2013) used in this study were developed from the locally available data (http://inputsurvey.dacnet.nic.in/districttables.aspx; FAI 2008, 2012) and could be of great relevance for fertilizer use planning at the local, regional and the national scale.

Soil Fertility: A Vital Component of Soil Quality

Soil quality is most often defined as "the capacity of the soil to function" (Karlen *et al*. 1997). The Soil Science Society of America (1995) defined "Soil Quality" as the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water quality, and support human health and habitation. It can be inferred that sustained productivity in terms of crop yields is a vital indicator of soil quality. The limitation imposed by inadequate nutrient status strips the soil off its "capacity to function or perform", and adequate availability of essential nutrients in the soil is critical for the sustained soil quality. Chauhan *et al*. (2012) suggested that the rice-wheat (RW) cropping systems of the Indo-Gangetic Plains (IGP) of the Indian sub-continent has not only resulted in mining of major nutrients (N, P, K and S) from the soil, but also has created a nutrient imbalance, leading to deterioration in soil quality. These authors commented that the quantities of nutrients removed by rice and wheat are greater than the amount added through fertilizers and other sources; and excessive nutrient mining of soils is one of the major causes of productivity fatigue experienced by the soils under the RW system. In case of potassium, besides low application rates, the mining situation is further aggravated by the removal of straw from the crop fields. It is estimated that K removal by crop residues represents approximately five times as much as is supplied by fertilizers (Chander 2011). Removal of crop residues from agricultural fields for competitive use, a common practice in the RW system, is expected to aggravate K mining from the soil even when optimum K is applied to the component crops. Similarly, because of continuous mining, the secondary and the micronutrient deficiencies in Indian soils are emerging as significant limitations to productivity of several crops and cropping sequences. Tandon (2013) compiled a large number of studies that showed significant yield responses to micronutrients in Indian soils. Such results suggest that

Table 1. Soil quality change (as % over fallow) under different management practices and cropping systems

Treatment/ Cropping system	Rice-wheat	Rice-lentil	Jute-rice-wheat
Control	-56.0	-8.0	-49.0
N-only	-	-11.7	-35.0
NPK-only	-10.8	-9.7	19.0
NPK +FYM	18.7	8.6	45.1

Source: Mandal (2005)

indeed the mining of nutrients have become a reason for soil quality concerns. Table 1 highlights the role of nutrients on maintaining the soil quality.

Researchers have identified soil organic carbon (SOC) content as one of the critical components of soil quality. Evidence from the long-term experiments have shown that application of nutrients at optimum rates either increased or maintained the SOC due to greater incorporation of biomass (Rekhi *et al*. 2000; Benbi and Brar 2009). Intuitively, one would be inclined to conclude that a decline in crop productivity would be accompanied by the decrease in SOC. However, the reported fatigue or decline in productivity in the Indo-Gangetic Plains (IGP) is not always accompanied by the decline of SOC. The SOC pool and its important fractions do not exhibit any systematic large-scale decline over the past few years at several sites within the IGP. This may indicate that decline in the productivity in the IGP does not arise from the oft-believed declining trend of the SOC status due to the prevailing global warming effects. In fact, Bhattacharya *et al*. (2007) noted an overall increase in SOC stock at the Benchmark spots, located in the IGP and the black soil (Vertisols) region in the semi-arid tropics, between 1980 and 2005. They also noted an increase in the level of soil inorganic carbon (SIC), which, they suggested, implies an initiation of chemical degradation of the soil. This probably means that the decline in the factor productivity in the regions of the country, and particularly in the IGP, has a direct correlation with the mining of essential plant nutrients rather than indirectly through nutrient management effects on SOC content of the soil (Sanyal 2014).

Besides the above studies, large body of experimental evidence are now available that showed *under-performance* of soils when soil fertility levels are downgraded due to *over-extraction* and *under-application* of nutrients. The following section highlights the nutrient mining aspects in crops and cropping systems reported from the on-station and the on-farm experimental sites across the country.

Experimental Evidences of Nutrient Mining

Evidences of Nutrient Mining under Long-term Experiments

A continuous mismatch between nutrient removal and replenishment, even at the recommended levels of fertilizer application, was evident in the long-term studies on various cropping systems. Long-term experiments conducted with rice-wheat systems in the IGP under the All India Coordinated Research Project on Integrated Farming Systems (AICRP-IFS) reveals that in general, additions of N and P in different locations were greater than their removal by the crops. As a result, the apparent balances of N or P were positive (Table 2). On the other hand, negative K balances were noted in all the treatments at all the locations studied. The magnitude of nutrient balance varies with crop production in a given location or among the locations. However, the effect of negative K balance may not be visible on available K content of soil, owing to high K supplying capacity of the illitic minerals-dominated soils of the IGP. As these soils are moderate to high in non-exchangeable K (Sanyal 2001; Bijay-Singh *et al.* 2004; Sanyal *et al*. 2009b) and contribution of this pool to the crop uptake is often greater than the available pool, the available K content may not be related to the decline in productivity, caused by the mining of K by the crop uptake (Tiwari and Nigam 1985). However, continued excessive depletion of K from the interlayer space of the illitic clays may lead to an irreversible structural collapse of these minerals, thereby severely restricting the release of K from such micaceous minerals (Sarkar *et al*. 2013). This would go a long way to impair the long-term soil fertility in respect of soil K, and is thus thoroughly unwarranted. The estimates of apparent N balance, which is positive at all the locations, may not also mean a sustainable input-output relation. In rice soils, the inclusion of N losses from rhizosphere by leaching, volatilization and denitrification in the nutrient balance calculation may render the N balances negative at all the locations. This suggests that the current practices of cropping and nutrient management are exhaustive in terms of N and K withdrawals leading to depletion of these nutrients from the native soil reserves.

Nutrient Balances under Sequences involving Legumes

Studies conducted under Mollisols of Pantnagar (Singh *et al*. 2002) and Typic Ustochrept soils of Modipuram (Singh *et al*. 2005) indicated that nutrient addition was relatively greater under the sequences

Table 2. Apparent nutrient balance (NPK) in rice-wheat system under long-term experiments conducted in IGP (5 year average)

Locations/	Annual addition (kg ha^{-1})			Annual removal (kg ha^{-1})			Apparent balance (kg ha^{-1})		
Treatments	N	P	K	N	P	K	N	P	K
Ludhiana (Trans-Gangetic Plain)									
Control	0	0	0	49.2	9.2	58.9	-49.2	-9.2	-58.9
50% NPK	120	19.7	27.3	98.1	21.5	121.3	+21.9	-1.8	-94.0
75% NPK	180	29.5	40.1	135.3	29.9	146.7	+44.7	-0.4	-106.6
100% NPK	240	39.3	54.5	178.7	38.5	192.4	+61.3	+0.8	-137.9
Kanpur (Upper Gangetic Plain)									
Control	0	0	0	50.1	8.3	50.2	-50.1	-8.3	-50.2
50% NPK	120	26.2	33.2	110.5	20.9	111.4	+9.5	+5.3	-78.2
75% NPK	180	39.2	49.8	132.8	24.3	141.6	+47.2	+14.9	-91.8
100% NPK	240	52.4	66.4	172.2	27.4	174.3	+67.8	+25	-107.9
Faizabad (Middle Gangetic Plain)									
Control	0	0	0	30.2	7.8	48.6	-30.2	-7.8	-48.6
50% NPK	120	26.2	33.2	96.2	22.3	123.4	+23.8	+3.9	-90.2
75% NPK	180	39.2	49.2	116.6	28.4	145.4	+63.4	+10.8	-96.2
100% NPK	240	52.4	66.4	155.3	35.1	181.6	+84.7	+17.3	-115.2
Varanasi (Middle Gangetic Plain)									
Control	0	0	0	26.2	3.8	44.3	-26.2	-3.8	-44.3
50% NPK	120	26.2	33.2	78.4	9.2	68.9	+41.6	+17	-35.7
75% NPK	180	39.3	49.2	130.1	15.1	128.8	+49.9	+24.2	-79.6
100% NPK	240	52.4	66.4	202.4	23.4	192.6	+37.6	+29	-126.2
Sabour (Middle Gangetic Plain)									
Control	0	0	0	36.9	7.8	52.4	-36.9	-7.8	-52.4
50% NPK	80	19.7	20. 5	76.2	19.7	120.6	+3.8	0	-100.2
75% NPK	120	29.5	30.7	132.3	24.2	142.2	-12.3	+5.3	-111.5
100% NPK	160	39.3	40.9	180.6	32.4	184.3	-20.6	+6.9	-143.4

Source: AICRP – IFS Reports (2006-2011)

involving green manures as compared with two-crop sequences. The apparent balance sheet revealed positive N balances under cereal-cereal system or sequences involving green manure as a component crop, whereas the sequences comprising a grain legume (monsoon or winter pulse) were negative (Table 3). The negative N balance for crop sequences involving grain legumes may be due to two reasons: (i) the N addition through fertilizer in the sequences involving grain legumes was lower than the 2- or 3-crop sequences involving both the cereal crops *i.e.* rice and wheat, though the N removal in the grain legume-based system was invariably greater, and (ii) the contribution of biological N fixation (BNF) in grain legumes was not included while computing apparent N balance. Earlier reports indicate that legumes may derive 54-70% of their N requirement through BNF in most cases (Awonaike *et al*. 1990). By taking N contributions from the BNF into account, the extent of negative N balance under legume system may be minimized to a level that it would not lead to an overall depletion in soil N reserve. Positive N balance under the sequences having *Sesbania* or mungbean green manure may be ascribed to sizable N additions through the incorporation of the corresponding green biomass.

Positive P balances under all the cropping system was ascribed to the lesser P removal in comparison to its addition through fertilizer and other sources (Table 3). When each component crop of an intensive production system receives P at the recommended rate, the apparent P balance remains positive in most growing situations (Swarup and Wanjari 2000; Dwivedi *et al.* 2011). The lower P uptake by the crops due to lower P use efficiency, caused by imbalanced application of other nutrients, and increased soil P build-up over the years is well documented by earlier reports (Singh *et al*. 2005, 2014b). However, such build-up of P is rather transient in nature and thus tends to be rather misleading to the planning of the long-term fertilizer P management strategies in the crops.

Negative K balance in all the sequences, especially in those without a green manure crop (Table 3) indicates long-term removal of soil K, which needs to be replaced by large inputs of K as fertilizer as well as through crop residue recycling. The legumes in these studies did not receive fertilizer K, and K appli-

Table 3. Apparent nutrient balance sheet for different crop sequences involving legumes

Sequences	Nutrient addition (kg ha^{-1})			Nutrient removal (kg ha^{-1})			Balance (kg ha^{-1})		
	N	P	K	N	P	K	N	P	K
Pantnagar[@]									
Rice-wheat (2)	510	97	165	370	68	228	+140	+29	-63
Rice-chicpea (2)	311	87	80	504	69	163	-193	+18	-83
Rice-wheat-*Sesbania* (GM) (2)	621	148	249	455	77	259	+166	+71	-10
Rice-wheat-maize+cowpea (f) (2)	642	133	222	519	76	351	+123	+57	-129
Rice-chickpea-maize+cowpea (f) (2)	439	124	145	581	75	308	-142	+49	-163
Modipuram									
Pigeonpea-wheat (3) [#]	572	170	124	616	107	209	-44	+63	-85
Cowpea-wheat (2)[!]	308	94	84	542	76	174	-234	+18	-90
Rice-wheat-cowpea (f) (3)[$]	712	154	284	594	69	428	+118	+85	-144

f = fodder; GM = Green Manure; values is parenthesis indicates years of cropping

Source: [@]Singh *et al*. (2002); [#]Singh *et al*. (2005); !Yadav *et al*. (2003); [$]Dwivedi *et al*. (2003)

cation rates to the other crops (wheat, rice and fodder) were not sufficient to meet the crop demand. On the other hand, sequences involving green mannuring had lower negative K balances than other crop sequences. The depletion in available K in the soil under the different sequences was smaller (data not reported) than the negative K balance, suggesting mobilization from the native soil K reserve (the non-exchangeable K pools) to the available K pool (Tandon and Sekhon 1988; Tiwari *et al*. 1992; Sanyal 2001; Sanyal *et al*. 2009b; Sarkar *et al*. 2013; Singh *et al*. 2013).

Nutrient Balance and Output:Input Ratio under Site-Specific Nutrient Management

A recent study conducted under intensively cultivated areas of the IGP reveals that the farmers apply N more than the recommended rates, optimum to sub-optimum P and neglect the application of K and other secondary and micronutrients (Singh *et al*. 2013). Application of nutrients as per the crop demands, with due consideration of the indigenous nutrient supply, not only enhances the grain yield with favoured economics, but also improves the soil nutrient status and the nutrient harvest index (Buresh *et al*. 2010; Singh *et al*. 2014a). Field experiments conducted under the Upper Gangetic Plain reveal that the site-specific nutrient management (SSNM) under the predominant cropping system, besides helping the judicious use of the applied nutrients (N, P and K), also minimizes their losses (particularly N) from the system. On the other hand, excessive N balance under farmers' fertilizer practice (FFP) as compared to SSNM suggests inefficient use of N by the crops, caused by imbalanced fertilizer use (Table 4). The higher (output: input) ratio and comparatively smaller apparent P balance under SSNM in all the cropping systems studied reveals that the SSNM treatment facilitated judicious P use and its higher accumulation in the crops. Whereas, lower output: input ratio under FFP shows the inefficient P fertilizer use by the crops.

Among the different nutrient management options, the highest negative apparent K balance was noticed with FFP, followed by that with the state recommended fertilizer rates (SR), while the least in SSNM (Table 4). Relatively higher negative K balance under FFP and the SR demonstrates the lack of K use in the existing farmers' fertilizer practices and sub-optional K recommendations at the state level as being unsustainable for the modern high yielding cultivars in the intensive cropping systems. Further, these results strongly bring out the necessity of developing the fertilizer recommendations, based on crop demand for a specified targeted yield, given the indigenous soil nutrient supplying capacity. However, negative nutrient balances even in the SSNM treatments in some locations suggest that there is further scope to improve nutrient rate determination using the SSNM principles. We shall discuss more about the SSNM approach as one of those designed to arrest partially the nutrient mining from soil under discussion here.

Depletion of Soil Nutrient under Best Management Practices (BMPs)

The nutrient output: input ratio (nutrient depletion factor) provides a measure as to whether and to what extent nutrient uptake exceeds the additions and provides gross estimates of possible depletion. Site-specific studies conducted across the rice-wheat growing regions of India indicates that crop uptake of P exceeds its input at 6 out of 10 locations, whereas the output: input ratio for K and S were more than 1.0 at

Table 4. Effect of nutrient management options on apparent nutrient balance sheet and output: input ratio under predominant cropping system of IGP after 3 year of cropping

Treatments	Nitrogen				Phosphorus				Potassium			
	Addition[@] (kg ha^{-1})	Removal (kg ha^{-1})	Apparent balance (kg ha^{-1})	Output: Input Ratio	Addition[@] (kg ha^{-1})	Removal (kg ha^{-1})	Apparent balance (kg ha^{-1})	Output: Input Ratio	Addition[@] (kg ha^{-1})	Removal (kg ha^{-1})	Apparent balance (kg ha^{-1})	Output: Input Ratio
Rice-wheat system												
FFP	1064	620	(+) 444	0.58	170	110	(+) 60	0.65	72	724	(-) 652	10.05
SR	932	731	(+) 201	0.78	191	122	(+) 68	0.64	357	899	(-)543	2.52
SSNM	938	872	(+) 66	0.93	173	148	(+) 24	0.86	630	1012	(-) 382	1.61
Maize-wheat system												
FFP	882	714	(+) 168	0.81	168	106	(+) 62	0.63	36	735	(-) 699	20.41
SR	741	737	(+) 4	0.99	168	126	(+) 42	0.75	312	860	(-) 548	2.76
SSNM	924	883	(+) 41	0.96	191	177	(+) 14	0.93	556	971	(-) 415	1.75
Pigeonpea-wheat system												
FFP	718	700	(+) 18	0.975	183	138	(+) 45	0.70	32	407	(-) 375	12.73
SR	557	780	(-) 223	1.400	166	145	(+) 21	0.87	202	457	(-) 255	2.26
SSNM	698	1045	(-) 347	1.497	188	166	(+) 22	0.88	556	514	(+) 43	0.92
Sesamum-wheat												
FFP	600	375	(+) 225	0.625	98	57	(+) 40	0.59	39	388	(-) 349	9.94
SR	489	447	(+) 42	0.91	135	72	(+) 63	0.53	231	505	(-) 274	2.18
SSNM	662	635	(+) 27	0.96	157	95	(+) 61	0.61	436	451	(-) 15	1.03
Groundnut-wheat system												
FFP	666	591	(+) 75	0.89	187	110	(+) 77	0.50	37	439	(-) 402	11.87
SR	519	688	(-)169	1.33	153	124	(+) 29	0.81	273	493	(-)220	1.80
SSNM	672	882	(-) 210	1.31	195	180	(+) 15	0.92	569	537	(+) 33	0.94
Sorghum-wheat system												
FFP	840	417	(+) 423	0.50	135	92	(+) 43	0.68	38	473	(-) 435	12.45
SR	746	548	(+) 198	0.73	171	122	(+) 49	0.71	260	581	(-) 430	2.24
SSNM	842	723	(+) 119	0.86	174	141	(+) 33	0.81	921	681	(-) 195	0.74

[@] Includes nutrient addition through rainfall, irrigation water and root+ stubbles during the course of study.

FFP = Farmers' fertilizer practice; SR = State recommendation rates of fertilizer application; SSNM = Site-specific nutrient management.

Source: Singh *et al*. (2014b)

Table 5. Nutrient depletion factor and nutrient uptake from soil reserve under rice-wheat system with BMPs* correcting all existing nutrient deficiencies except that of the indicated nutrients

Location	Rice-wheat system yield (t ha^{-1})	Nutrient depletion factor (output: input ratio)			Depletion of soil nutrients from soil reserve (kg ha^{-1})		
		P_2O_5	K_2O	S	P_2O_5	K_2O	S
Sabour	13.8	1.74	1.86	1.20	88	261	42
Ranchi	10.4	0.73	1.09	2.04	63	205	41
Ludhiana	16.1	1.36	2.29	2.07	126	354	58
Palampur	9.8	1.70	1.83	1.35	74	226	36
R.S.Pura	13.2	0.67	1.71	1.48	94	301	45
Faizabad	12.3	0.97	1.52	1.48	80	252	39
Kanpur	14.6	1.03	1.48	2.27	66	247	43
Modipuam	16.7	1.98	1.63	3.50	100	294	58
Varansi	12.1	1.35	1.50	1.60	65	221	38
Pantnagar	12.4	0.77	1.45	2.02	67	220	42

*Best management practices
Source: Tiwari *et al*. (2006)

all the locations (Table 5), indicating a stress on soil K and S supplies. Further, these results (Table 5) become more interesting when nutrient uptake for P, K and S was furnished from the soil native reserves in the absence of their external input. Results reveal that the highest removal of the soil nutrients accompanied the highest productivity level (Table 5). For example, at Ludhiana, exclusively soil-derived maximum nutrient uptake led to the highest productivity, whereas the acid soils of Ranchi could support only 65% of the productivity of the Ludhiana, with the concomitant soil-derived nutrient removal being also much less (Table 5). These results bring out the possible depletion of a nutrient from the native soil reserves when its application is omitted and yet high grain yields are targeted. It is very likely that on a longer-term basis, these soil contributions will decrease due to continued soil mining. It is thus obvious that such management practices should not be allowed to continue endlessly, while planning for obtaining high yields of the crops in a sustainable agricultural production system.

On-farm Nutrient Use and Nutrient Mining at Cultivators' Field

An on-farm study conducted under AICRP-IFS at the cultivators' field indicates that the prevailing fertilizer management practices by the farmers are skewed towards N (Table 6). Applications of P are sub-optimal and in many cases far below the state recommendation of P use in crop/cropping system. Use of K, secondary and micronutrients are almost completely neglected. On-farm study conducted across the major cropping systems under the aegis of the AICRP-IFS indicates that the farmers are applying 38.8, 57.1 and 93% lesser P, K and micronutrients, on an average, respectively as compared to the recommended doses of these nutrients (AICRP-IFS Reports). Such imbalance in fertilizer application leads to huge yield gap between the yield obtained with the application of the recommended nutrient doses (macro and micro) and that with the farmers fertilizer management practice (Figure 1). Further, partitioning of such yield gap between the major (NPK) and the micronutrients indicates that in cereal–cereal system, contribution of NPK in bridging the yield gap was higher (72 to 86%) as against the micronutrients (14 to 28%). However, in rice-green gram system, the contribution was almost equal (52 and 48%, respectively). This highlights the variation of the nutrient requirement specificity with crops as well as cropping systems.

A careful perusal of the data presented in table 6 clearly indicates that nutrient mining is more acute with FFP, caused by the imbalanced nutrient use (particularity the neglect of K). Further, the prevailing SRs are also unable to prevent nutrient mining (NPK) and the situation gets worse by the under-application of the deficient secondary and micronutrients. Here it is pertinent to mention that nutrient mining is more acute under high yield-potential hybrids. Presently, more efficient rice and wheat cultivars are substantially replacing the relatively older varieties in the vast tract of the upper and the middle IGP, the former being more efficient nutrient user in respect of utilizing them better for enhanced biomass production at essentially the same rates of the extraneous addition of the fertilizers. Thus, most of the state recommen-

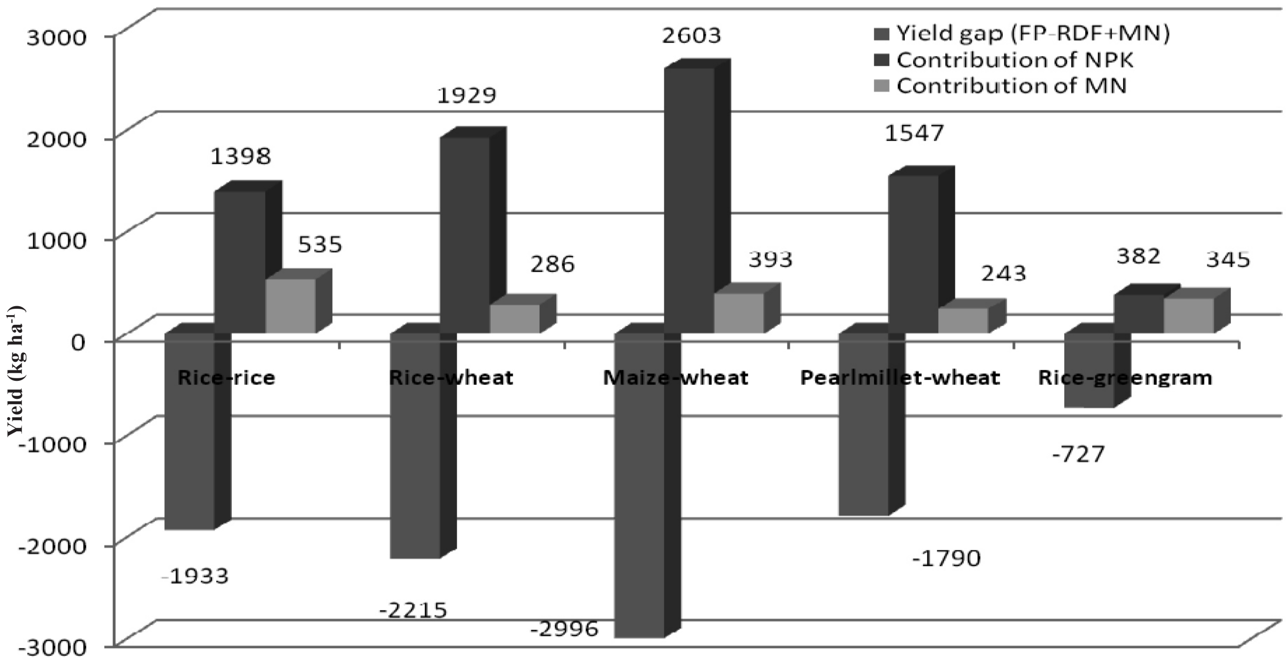

Fig. 1. Yield gap between the recommended nutrient package (RDF) and the farmers' fertilizer management practices (FP) along with the contribution of the major and the micronutrients (MN) to bridge the yield gap under predominant cropping systems
Source: Gangwar *et al.* (2013)

dations for the newly developed high yielding hybrids are quite similar to those for the traditional cultivars supporting the optimum to sub-optimum yield. However, this suggests that these better yielders indulge in even *greater withdrawal* from the native soil nutrient pools, thereby rendering the adequate nutrient replenishment in soil more of a challenge and the aforesaid nutrient mining more acute. If these estimates are any indication, it becomes imperative that to sustain the soil system, the present trend has got to be reversed by adequate replenishment of the soil reserve.

Doubtless, as stated above, the higher demands for food, feed and fiber at a reduced availability of resources such as land, water and nutrient would further emphasize the importance of using the nutrient (resource) efficient cultivars. Fageria *et al*. (2008) defined the *nutrient efficient plants as those which produce higher yields per unit of the nutrient, applied or absorbed, than other plants (standards) under similar agro-ecological conditions*. For instance, Richardson (2001) suggested exploitation of the gene technologies for manipulating the structure and function of plant roots for improved acquisition of soil P. In particular, the selection of plants for the improved root morphology (Lynch 1995) including root branching may also facilitate such increased efficiency of P. The cloning and characterization of plant and fungal phosphate transporter genes (Fageria *et al***.** 2008) may further provide new possibilities for increasing plant P uptake (Richardson 2001). Admittedly, the present authors could not find systematic studies, using, for instance the tracer technology, which would establish that such increased uptake of the plant nutrients by the improved crop cultivars has basically tapped the applied extraneous nutrient carrier or else the native soil source or both. Indeed if such increased uptake has been attributed to both the extraneous source and the native soil, the question arises as to what could be the relative contributions from these two sources?

Notwithstanding what is stated above, and despite intense research work during little over the last three decades or so, there has been limited success in releasing the nutrient efficient cultivars, chiefly for the rather less understood interactions of the genetics of plant responses to nutrients, as well as such plant interactions with the environmental variables. Indeed in this context, Fageria *et al*. (2008) brought out the complexity of the genes responsible for nutrient use efficiency for macro- and micronutrients which gets further complicated owing to limited collaborative efforts till date between the breeders, on one hand, and the soil scientists, physiologists and agronomists, on the other.

Table 6. Nutrient use and removal at cultivators' field

Location/ cropping system	Treatment	Nutrient addition ($kg\ ha^{-1}$)			Nutrient removal ($kg\ ha^{-1}$)			Apparent balance ($kg\ ha^{-1}$)		
		N	P	K	N	P	K	N	P	K
Rice-wheat/ Kaushambi,	FFP	206.0	28.4	0.0	133.0	22.0	150.0	73.0	6.4	-150.0
UP (24)	SR	220.0	48.0	74.7	186.0	35.0	160.0	34.0	13.0	-85.3
	SR + M	220.0	48.0	74.7	204.0	40.0	174.0	16.0	8.0	-99.3
Rice-rice /Warangal,	FFP	298.0	60.3	70.6	168.0	47.0	172.0	130.0	13.3	-101.5
AP (24)	SR	240.0	52.4	66.4	185.0	52.0	189.0	55.0	0.4	-135.6
	SR + M	240.0	52.4	66.4	199.0	56.0	202.0	41.0	-3.6	-135.6
Pearl millet-mustard/	FFP	114.0	37.1	0.0	171.0	45.0	104.0	-57.0	-7.9	-104.0
Deesa, Gujrat (18)	SR	130.0	39.3	54.0	193.0	51.0	116.0	-63.0	-11.7	-62.1
	SR + M	130.0	39.3	54.0	200.0	54.0	122.0	-70.0	-14.7	-65.1
Pearl millet-wheat/Thesra,	FFP	130.0	34.9	0.0	129.0	28.0	65.0	1.0	6.9	-65.0
Gujrat (18)	SR	200.0	43.7	83.0	194.0	43.0	95.0	6.0	0.7	-12.0
	SR + M	200.0	43.7	83.0	200.0	44.0	101.0	0.0	-0.3	-18.0
Maize-bengal gram/ Gadak,	FFP	80.0	38.0	0.0	138.0	26.0	133.0	-58.0	12.0	-133.0
Karnataka (24)	SR	110.0	32.8	20.8	142.0	28.0	169.0	-32.0	4.8	-148.3
	SR + M	110.0	32.8	20.8	156.0	32.0	181.0	-46.0	0.8	-160.3
Rice-green gram/Kakdwip,	FFP	52.5	26.6	34.0	130.0	22.0	129.0	-77.5	4.6	-95.0
WB (18)	SR	100.0	34.9	66.4	138.0	26.0	161.0	-38.0	8.9	-94.6
	SR + M	100.0	34.9	66.4	148.0	29.0	176.0	-48.0	5.9	-109.6
Maize-wheat/Kangra,	FFP	50.0	14.0	21.6	678.0	17.0	53.0	-18.0	-3.0	-31.4
HP (18)	SR	170.0	37.6	58.1	130.0	30.0	89.0	40.0	7.6	-30.9
	SR + M	170.0	37.6	58.1	135.0	33.0	97.0	35.0	4.6	-38.9
Cotton-pearl millet/ Deesa,	FFP	202.0	37.8	0.0	287.0	46.0	85.0	-85.0	-8.2	-85.0
Gujrat (18)	SR	320.0	43.7	83.0	324.0	52.0	91.0	-4.0	-8.3	-8.0
	SR + M	320.0	43.7	83.0	378.0	53.0	102.0	-58.0	-9.3	-19.0

Source: AICRP-IFS Reports (2011-12)

Overview of Current Knowledge and Addressing Nutrient Mining

A review of the existing literature underlines a three-tier approach for addressing the nutrient mining issue in Indian soils as discussed below:

Moving Away from a Generalized to a Site Specific Nutrient Management Approach

Balanced fertilization in India has been accepted as application of N, P_2O_5 and K_2O in the ratio of 4:2:1. Indeed such ratio in actual practice in Indian agriculture varied with time, with the one closest to the so-called ideal ratio being noted as 4.3:2.0:1.0 during 2009-10 (FAI 2013). Such a uniform prescription across the board, without taking any cognizance of the inherent features of the soil, the type of crops grown as well as the cropping sequences on different soils under varied prevailing climatic conditions, is a major reason for nutrient mining as well as economic losses for farmers. Indeed, it appears unlikely that a single, all pervading ratio can justify the concept of balanced fertilization across the country. Doubtless, such a concept of a uniform fertilizer application schedule appears to be in direct conflict with the very principles of the SSNM. Ideally, an all-India indicator of the desired balanced fertilizer application should emerge as a weighted average of state or even agro-ecological zone level indicators and should go beyond the realm of NPK only (Sanyal *et al*. 2009a).

Whatever may be the origin of 4:2:1 ratio, farmers in India do not follow it under most farm situations. The application of N fertilizers tends to be preferred by farmers, because of their relatively low cost per unit of nutrient, their widespread availability, and the quick and evident response of the plant. Phosphorus and K use are low as compared to N and the secondary and the micronutrients are generally omitted from the fertilization schedule, leading to the possibility of nutrient mining from soils. Balanced fertilization, in its true sense, provides the required nutrients to the plants in a balanced manner, taking account of the nutrient supplying capacity of the soils and the nutrient requirement of the crop. The concept of balanced fertilization, when applied in a location-specific manner incorporating site-specific details of the location, led to the development of the SSNM. It strives to enable the farmers to adjust fertilizer use in their fields to meet the deficit between a high-yield crop and the nutrient supply from the naturally occurring indigenous sources in the soil. It recognizes the inherent spatial variability associated with fields under crop production and ensures that all the required nutrients are applied at proper rates and in proper ratios commensurate with the crop's nutrient needs. The universality of the principles of the SSNM approach has led to its application to different crops and agro-ecologies (Majumdar *et al*. 2014). The in-built algorithms of SSNM cut down over- and under-use of fertilizers and significantly reduce the probability of nutrient mining. So conceptually moving from a generalized nutrient management approach, based on some arbitrary ratio, to a rational site specific approach would be the starting point of addressing the nutrient mining issue.

Critical Assessment of Field Specific Nutrient Input-Output Balance

Nutrient input-output balance in an agricultural field is one of the most critical knowledge requirements for implementing the aforesaid SSNM. Nutrient balance studies are common in literature and serve different purposes, ranging from estimating national/regional fertilizer requirement to the estimate of the nutrient requirement in specific field for individual crop or cropping sequences (Majumdar and Sayanarayana 2011). The following example from Buresh *et al*. (2010) illustrates the methodology, followed in estimating K balances in agricultural fields for single crop as well as cropping systems involving cereals. The essential components of such K balance calculations included contributions (inputs) from the retained residues, irrigation water and added organic matter and loss (output) of K from the system through leaching and export through the grain of the component crops.

Buresh *et al*. (2010) used the following equations to estimate the K balance in continuous rice, rice-wheat and rice-maize cropping systems:

$$\text{K balance for rice} = K_W + K_{OM} + K_{CRr} - K_L - (GYr \times RIE_{Kr}) \quad \text{…[1]}$$

$$\text{K balance for rice–wheat or rice–maize} = K_W + K_{OM} + K_{CRr} + K_{CRwm} - K_L - (GYr \times RIE_{Kr}) - (GY_{wm} \times RIE_{Kwm}) \quad \text{…[2]}$$

where, K balance and each input are expressed in kg ha^{-1}, K_W is K input from irrigation water for an entire cropping cycle, K_{OM} is K input from the added organic materials, K_{CRr} is K input with the retained residues of rice, K_{CRwm} is K input with the retained residues of wheat or maize, K_L is K loss by percolation or leaching in kg ha^{-1}, GY_r and GY_{wm} are the targeted grain yields in t ha^{-1} for rice and wheat or maize, RIE_{Kr} is the reciprocal internal efficiency of rice for K , and RIE_{Kwm} is the reciprocal internal efficiency of wheat or maize for K. The K input from residues for a crop (K_{CR}) was determined from the amount and the nutrient content of the above-ground crop biomass retained in the field after harvest using the following equation:

$$K_{CR} = GY \times RIE_K \times (1 - HI_K) \times CRR \quad \text{…[3]}$$

where, HI_K is the K harvest index for a crop, expressed as kg nutrient in grain per kg nutrient in total above-ground dry matter, and CRR for a crop is the fraction of the total crop residue retained in the field after harvest.

The results from this study suggested that retention of rice residues in continuous rice-rice systems is a must for maintaining a positive K balance in the soil. The K balance was found to be positive only at 100% residue retention even at an assumed K addition of 20 kg ha^{-1} through irrigation water (Buresh *et al*. 2010). However, the *K balance was strongly negative at 15-40% of residue retention, which is indeed the prevailing situation in India*.

Rice-wheat system is practiced extensively in the IGPs. Farmers in this area use irrigation water, which may contain high amounts of K. The estimated addition of K through irrigation in certain areas could be as high as 80-100 kg ha^{-1}. At the same time, the soils in this region are light textured and percolation losses are also very high. So the potential for percolation loss of K, added through irrigation water and released from non-exchangeable K pools of minerals, can also be high. This also suggests that the K balance in intensive rice-wheat systems in the North West India, where the system grain yield can reach as high as 12 t ha^{-1} with an equivalent amount of non-grain biomass, could be highly negative even at the high rate of addition of K through irrigation water, thereby advocating the external addition of K in order to sustain the productivity. Highly variable K content in irrigation water and variability in residue management across the IGP will require very site-specific estimation of such balance in the rice-wheat system.

The emerging rice-maize system offers a major challenge to maintain the K balance in the soil. Among the major reasons, the ecosystems where rice-maize systems are thriving (Eastern India, Bangladesh, South India) generally do not have high K content in irrigation water and the retention of rice and maize residues in the field is not a common practice. Besides, the dry matter yield of rice-maize system is usually much higher than rice-rice and rice-wheat, causing thereby extraction of large amounts of nutrients from the soil. In the absence of effective residue retention practices, large amount of K is exported out of the field with the harvested product and the residues. This suggests that larger K deficits and higher fertilizer K requirement could be anticipated in rice-maize system (Buresh *et al*. 2010). The authors also reported on similar assessment mechanisms for P balance in their article (Buresh *et al*. 2010).

Approaches for Determination of Fertilizer Rate

Witt and Dobermann (2004) suggested that the expected yield gain from the added nutrient or estimated nutrient balance can be used to determine the fertilizer requirements to achieve a targeted yield. The following section provides an example of fertilizer rate calculations based on yield gain, from nutrient input-output balance (full maintenance) or from a combined yield gain-maintenance approach using K as the target nutrient.

In the yield gain approach, the fertilizer K (FK) required to achieve a targeted yield (GY, expressed in t ha^{-1}) is a function of the expected yield gain from the added nutrient, the reciprocal internal efficiency (RIE) for the nutrient, and the use efficiency of the applied nutrient:

$$FK = (GY - GY_{0K}) \times RIE_K/RE_K \quad \text{....[4]}$$

where, GY_{0K} is grain yield in t ha^{-1} in the K omission plot, RIE is the reciprocal internal efficiency and RE_K is the recovery efficiency of the applied K, expressed in kg kg^{-1}.

Fertilizer K and P requirements to achieve a targeted yield can also be estimated through nutrient input-output balances. Witt and Dobermann (2004) used the following equations based on the nutrient balance to estimate fertilizer K (FK) requirement (in kg ha^{-1}) for a crop with full maintenance of soil K:

$$FK = (GY \times RIE_K) + \{(GY - GY_{0K}) \times RIE_K\} - K_{CR} - K_W - K_{OM} + K_L \quad \text{...[5]}$$

where, K_{CR} is K input with the retained residues, while the other inputs and losses are as defined for equations 1 to 3. Inputs and losses are all expressed in kg ha^{-1}. Witt and Dobermann (2004) included the expected yield gain from the addition of a nutrient ($GY - GY_0$) in the determination of fertilizer requirements to ensure that the fertilizer K rate in the presence of a yield gain were increased by the amount of the nutrient uptake deficit to slowly build-up the native soil nutrient supplies.

In the yield gain approach for determining fertilizer K requirement, fertilizer K is only applied when a crop response to the nutrient is certain. A distinctly undesirable feature of the fertilizer K rate determined by the yield gain approach is higher K depletion at high than low target yields. Buresh *et al*. (2010) found that fertilizer K requirement determined by the yield gain approach (Equation 4) increased with increasing target yield; but the K rate did not increase sufficiently fast to prevent increasing depletion of soil fertility with increasing yield within the ranges of the yield gain common for irrigated rice. This could accelerate the onset of nutrient limitations and subsequent declines in productivity in the existing high-yielding areas. At the same time, the full maintenance approach can result in relatively large application of K that may not be profitable at no or low yield gain. Buresh *et al*. (2010) examined two options using nutrient balances to calculate the fertilizer K rates based on partial maintenance with gradual drawdown or depletion of soil K rather than full maintenance of soil K. In one option with partial maintenance, fertilizer K requirement is calculated as a fraction of the full maintenance (FM) as shown in equation 6:

$$\text{FK with fractional K depletion} = (GY \times RIE_K - K_{CR} - K_W - K_{OM} + K_L) \times FM \quad \text{...[6]}$$

The other option with partial maintenance allows depletion of K from soil reserves up to a threshold limit (K_S in kg ha^{-1}), which is treated as an input in the nutrient balance:

$$\text{FK with limited K depletion} = GY \times RIE_K - K_{CR} - K_W - K_{OM} - K_S + K_L \quad \text{...[7]}$$

When FM = 1 or when $K_S = 0$, the calculated fertilizer rates for a nutrient ensure full maintenance with no depletion of the nutrient.

In the first option (Equation 6), a fraction of the nutrient required for full maintenance of the nutrient input-output balance was allowed to be drawn from the soil nutrient reserve while the rest is applied externally. Buresh *et al*. (2010) showed that this option of partial balance has the risk of higher nutrient depletion and declining productivity at a higher yield target compared to the lower yield targets. Instead, the limited K depletion approach (Equation 7) provides an option of comparable nutrient depletion across yield levels and the nutrient balances are never more negative than the limit for drawdown of soil nutrient reserves (KS), rendering it more attractive than the fractional K depletion approach.

Buresh *et al*. (2010) also combined the partial maintenance and yield gain approaches for determining the fertilizer K rate when crop response to the nutrient is certain:

$$\text{FK with fractional K depletion} = (GY \times RIE_K - K_{CR} - K_W - K_{OM} + K_L) \times FM) + (GY - GY_{0K}) \times RIE_K/RE_K) \quad \text{...[8]}$$

FK with limited K depletion = $(GY \times RIE_K - K_{CR} - K_W - K_{OM} - K_S + K_L) + (GY - GY_{0K}) \times RIE_K/RE_K)$ …[9]

Buresh *et al.* (2010) showed that when the yield gain to applied K is relatively small, fertilizer requirements can be determined with only a partial maintenance approach. When the yield gain is more pronounced, a partial maintenance plus yield gain approach can be considered for determining the fertilizer requirements.

In a recent paper, Singh *et al*. (2014a) used the nutrient input-output balance to come up with nutrient recommendations for the targeted yield of rice-wheat cropping system (RWS) in the IGP.

The optimum nutrient doses for the RWS in IGP were worked out based on the plant nutrient demand for a targeted yield and nutrient balance calculations. On-farm data were used to estimate the reciprocal internal efficiencies (RIE) of rice and wheat (Buresh *et al*. 2010). These values were subsequently combined with the indigenous nutrient supply (INS) and yield gains from the added nutrients to determine the nutrient requirements for rice and wheat for a predetermined yield target. The components of INS calculations included nutrient (N, P and K) contributions from soil available pool, irrigation water, and rainfall, and their availability (%, efficiency) to the crop. The following equation was used to estimate the nutrient (N, P and K) balance under the RWS.

$B_{n(rw)} = \{(IW_n \times Eff) + (CR_n \times Eff) + (RF_n \times Eff) + (S_n \times Eff)\} - \{(GY_r \times RIE_{nr}) + (GY_w \times RIE_{nw})\}$ …(10)

where, B_n is the nutrient balance (N or P or K; kg ha^{-1}), and the IW_n, CR_n, RF_n and S_n are the nutrient (N or P or K) contribution from irrigation water (IW), crop residue, rainfall and soil during the entire rice–wheat cropping cycle, respectively. The term "Eff" is the efficiency (%) of nutrients from different components of INS in terms of their availability to the crops. The GYr and GYw are attainable grain yields (t ha^{-1}) of rice and wheat, respectively, while RIE_{nr} and RIE_{nw} were the reciprocal internal efficiencies for rice and wheat for N or P or K, respectively.

The nutrient contributions from IW and RF (kg ha^{-1}) were estimated using total amount of irrigation water applied/rainfall received (ha-cm) during the rice–wheat cycle, and their N, P and K content. Average available soil N, P and K content (kg ha^{-1}) at the start of the study across the locations was used as contribution from soil. The nutrient input from residues of a crop (CR_n) was determined from the amount and nutrient content of the above ground crop biomass retained in the field after harvest and expressed in kg ha^{-1}. The total fertilizer nutrient requirement (kg ha^{-1}) for the RWS ($F_{n(rw)}$) was worked out as follows:

$F_{n(rw)} = B_{n(rw)} RE_{n(rw)}^{-1}$ …(11)

where, $F_{n(rw)}$ is the fertilizer nutrient (N or P or K) requirement for rice (kg ha^{-1}) and $RE_{n\,(rw)}$ is the recovery efficiency (%) of the nutrient N, P and K under rice and wheat crop. Using above equation, Singh *et al*. (2014a) estimated the rates of fertilizer nutrient (N or P or K) requirement for 10 t ha^{-1} hybrid rice and 6 t ha^{-1} wheat grain yields as 300 kg N, 52.3 kg P and 197.6 kg K ha^{-1}, respectively, and applied the same at several locations of the IGP and the neighboring regions that improved the crop yields, nutrient use efficiency and profitability over the existing practices.

Knowledge Gaps and Future Initiatives

Reciprocal Internal Efficiency

The Reciprocal Internal Efficiency (RIE) appears prominently in the above section as a major contributor to the nutrient balance equations and for determining the nutrient rates using different approaches. The RIE has its origin in the modified QUEFTS (*Quantitative Evaluation of the Fertility of Tropical Soils*) model (Janssen *et al*. 1990; Witt *et al*. 1999) that assesses the relationship between the grain yield of rice and the corresponding nutrient accumulation as a function of the climatic yield potential and the supply of the three macronutrients. The underlying principle is that the relationship between grain yield and nutrient accumulation may be described as a function of the climatic yield potential and the supply of the three macronutrients N, P and K. In a situation where crop growth is not limited by water supply or pest infestations, biomass production is mainly driven by the nutrient supply (Dobermann and Witt 2004). For balanced nutrition, the QUEFTS model assumed *a linear relationship between the grain yield and the plant nutrient uptake, that is, a constant internal efficiency (of the major plant nutrients N, P and K) up to yield targets of nearly 70-80% of the yield potential*. As yields approach the potential yield, the internal nutrient efficiencies decline since the relationship between the grain yield and the nutrient uptake enters a non-linear phase (Majumdar *et al*. 2014). In the QUEFTS model, two boundary lines described the minimum and maximum internal efficiencies (IEs, kg grain per kg nutrient in the above-ground plant biomass dry matter) of N, P and K. Indeed, in the domain bound by such minimum and maximum IEs of N, P and K in the plant across a wide range of yields and nutrient status (for more than 2000 entries), the balanced N, P and K uptake requirements for 1000 kg of rice grain yield were estimated from the respective envelope functions as being 14.7 kg N, 2.6 kg P and 14.5 kg K, that is, 68.0 kg grain kg^{-1} N, 385 kg grain kg^{-1} P and 69.0 kg grain kg^{-1} K, respectively, for the aforesaid linear phase. The corresponding borderlines for describing the minimum and maximum internal efficiencies were estimated at 42 and 96 kg grain kg^{-1} N, 206 and 622 kg grain kg^{-1} P and 36 and 115 kg grain kg^{-1} K, respectively (Witt *et al*. 1999; Dobermann and Witt 2004; Majumdar *et al*. 2014). These parameters were found to be valid for any site in Asia where the modern rice varieties with a harvest index of about 0.45-0.55 were grown. Similar work was later done for maize (Setiyono *et al*. 2010) and wheat (IPNI, Unpublished data, cited by Majumdar *et al*. 2014).

Furthermore, Chuan *et al*. (2013) also estimated the balanced nutrient requirement for wheat in China as being essential to manage the nutrient application more effectively for increasing the crop yields with reduced negative environmental impact, by way of using the QUEFTS model. Datasets pertaining to N, P and K treatments from the winter and the spring wheat growing regions in China during 2000-2011 with harvest index ≥ 0.40 were collected to obtain the relationship between the grain yield and the nutrient uptake. The minimum and maximum IEs for such wheat crop turned out to be 28.8 and 62.6 kg grain kg^{-1} N, 98.9 and 487.4 kg grain kg^{-1} P, and 23.0 and 112.9 kg grain kg^{-1} K. In this case, the above stated QUEFTS model predicted a linear–parabolic–plateau curve for the balanced nutrient uptake at several target yields. The linear phase in this case was noted to continue up to 60–70% of the potential yield, and 22.8 kg N, 4.4 kg P and 19.0 kg K were required to produce 1000 kg grain. The corresponding N: P: K ratio was 5.18:1:4.32 and the corresponding IEs were 43.9, 227.0 and 52.7 kg grain per kg N, P and K, respectively. They further estimated the relationship between the grain yield and the nutrient uptake for suggesting the fertilizer application, avoiding excess or deficient nutrient supply. Indeed, the validation of the QUEFTS model through the field experiment confirmed that this approach may be used as a practical tool for the ***Nutrient Expert®*** decision support system to make fertilizer recommendations (Chuan *et al*. 2013).

With these observations at hand, the present authors wonder as to the fact that the minimum internal nutrient efficiency of the major plant nutrients for balanced nutrition turns out to be quite lower than the corresponding values for these nutrients under the constant internal efficiency range of actual grain yield *vis-à-vis* the respective potential values. Thus, for the cited case of rice cultivation in Asia, the minimum internal nutrient efficiency for K turns out to be about 50% lower than that for K in the above stated linear phase, while for N and P, the respective lowering of these values were to the extents of about 40% and 46%.

Indeed, the above mentioned approach, by itself, does not spell out much in respect of the nutrient depletion from the soil subjected to intensive cropping practices, nor about nutrient mining by crops. Further, Dobermann and Witt (2004) highlights that these relationships as in the QUEFTS approach assume that in a situation of nutrient depletion (nutrient balance <0), *nutrients in the depleted pools contributing to IPS (indigenous P supply) and IKS (indigenous K supply) are largely* ***replenished*** *by those from* ***other soil pools*** so that the net loss of IPS or IKS is small (1–5% per crop). The approach apparently does *not* lend itself to identify these *other soil pools*, nor does it elaborate the overall nutrient loss, *i.e*., ***nutrient mining.*** One draws support for such supposition from the fact that Dobermann and Witt (2004) themselves suggested the need for *major future research* endeavour for validating these (QUEFTS) model-predicted changes in IPS and IKS by way of placing the omission plots into the SSNM plot. However, these authors have already discussed above as how such approach was later extensively resorted to by Buresh *et al*. (2010) in addressing the issue of nutrient mining from soil and the different restorative measures.

With such discussion in place, the question that comes to mind is that if the aforesaid linear phase of the internal nutrient efficiency of N, P and K persists up to as much as 70-80% of the potential yield of the rice cultivars under cultivation in Asia (Dobermann and Witt 2004), presumably under irrigated rice ecosystem, which one of the envelope of the internal nutrient efficiency curves, bound by the two boundary lines (describing the minimum and maximum internal efficiencies), defined by the QUEFTS model, would be put to use for making further progress in estimating the fertilizer requirement to support a targeted yield of a crop in a given soil under a specific scenario of crop residue retention in the field, irrigation water source, and so on. Is there any possibility of under- or over-use of fertilizers in such cases? In other words, does this render the soil ***poorer or else richer*** than what one would think in terms of the available methodologies to estimate the withdrawals from the soil?

Nutrient Content in Irrigation Water

Nutrient input from irrigation water and losses through leaching features prominently in nutrient balance equations that helps estimate fertilizer requirement. Irrigation water contains essential plant nutrients, particularly K, which upon addition to soil improves soil fertility (Singh and Bishnoi 2001). Presence of K in irrigation water constitutes an important source of indigenous supply of K to plants. The K input from irrigation water depends primarily on (a) K concentration in the added water and (b) the quantity of water added during the entire crop production cycle, *i.e.*, from the onset of land preparation to harvest (Bijay-Singh *et al*. 2004). However, K concentration in irrigation water varies with different sources of irrigation (canals, bore wells, farm ponds, community tanks, open wells, *etc*.) and also with its time of application at different stages of crop growth. This leads to uncertainty in quantifying the K input to a specified crop (Yadvinder-Singh *et al*. 2005). Nature of the parent material, presence of soluble minerals releasing K into water aquifers and surface run-off of the top fertile soil along with irrigation water increase the variability in K content in irrigation water from ground water sources. In a recent study (Satyanarayana *et al*. 2013), K concentrations in irrigation waters varied significantly among the surveyed regions. Such variations, both at the spatial and the temporal scales, lead to uncertainties in estimating the contribution of K from irrigation water for a specific crop in a given region. Studies have assumed blanket irrigation water K contents while estimating fertilizer K requirements of crops, which may lead to inadequate K application to crops. Potassium content of irrigation water from studied areas showed that the K contribution of irrigation water is far below the total crop K requirement and that external K application through fertilizer sources would be required to sustain and improve the crop yields, while maintaining soil K fertility levels as well. Besides, while discussing input of K from irrigation water, it must be understood that all the K input to the field *via* irrigation water may not be available to the plants. A portion of the K and other basic cations added to the field through irrigation water may be lost *via* leaching from fields with adequate drainage. Leaching losses of K can be substantial in highly permeable soils with low cation-exchange capacities. Yadvinder-Singh *et al*. (2005) found that leaching losses of K were 22 and 16% of the applied K in sandy loam and loamy soils, respectively, maintained at submerged moisture regimes. The above discussion suggests significant knowledge gap in proper assessment of nutrient content in irrigation water at a spatial and temporal scale in India. Besides, the potential losses of the added nutrients from different soil types through leaching need to be assessed under variable growing conditions. This will help in better assessment of the nutrient inputs, particularly K, from irrigation water to estimate the fertilizer requirement of crops.

Crop Residue Management

Crop residues, in general, are parts of the plants left in the field after crops have been harvested and threshed. The recycling of crop residues can significantly add to the nutrient input in a cropping system (Mandal *et al*. 2004). In general, farmers remove crop residues from the fields for other competitive use such as animal feed, *etc*. This aggravates the nutrient mining from soils. Buresh *et al*. (2010) analyzed several scenarios in cereal systems to show the critical importance of crop residue retention in agricultural fields to maintain the nutrient balance. The study showed that K balance in rice-wheat system can be negative even at an estimated addition of 125 kg K ha^{-1} from irrigation water if only 15% of rice and wheat residues are retained in the field. The K balance becomes neutral only at 100% retention of the rice residues with 125 kg K ha^{-1} addition per hectare through irrigation water. However, additions of crop residues in the agricultural fields give rise to competitive microbiological processes that can significantly influence nutrient dynamics in the soil. For example, fields receiving crop residues may cause an initial spurt of microbial activities that may immobilize nitrogen leading to competition between crop and the microbes present in the soil. Besides, the nutrients present in crop residues have variable mineralization rates that may affect their availability to the succeeding crop. A fairly recent study by Yadvinder-Singh *et al*. (2010) clearly highlighted the issue in the rice-wheat cropping system where the authors showed that the surface-placed residue presented a slow decomposition, which does *not* contribute N to wheat and might even immobilize soil N. They suggested that adjustments in timing and rate of fertilizer N are likely necessary to optimally supply N to crops receiving residues over long term. This study also showed that while rice residue (either placed at surface or buried into the soil) is not a potential source of N and P for wheat over short-term, it can supply significant amount of potassium to wheat.

The present authors consider that there are several researchable issues in the domain of crop residue management that are critical. An assessment of how crop residues could be equitably distributed for different competitive uses, such as between animal feed requirement and nutrient recycling in fields, may provide options for farmers to retain at least part of the residues in the field. Critical estimation of the rate of mineralization of crop residues with different C:N ratios under varying agro-climatic conditions and management scenarios would also be required for assessing the nutrient availability from crop residues for the nutrient balance calculations.

A National Soil Data Repository

It goes without saying that a national portal for soil data repository is a critical requirement for assessing soil nutrient mining. The present authors strongly believe that a national-level initiative to develop and maintain a soil data repository will allow tracking of soil fertility changes in intensive cropping regions over time. At this point, such databases are fragmented and maintained by several organizations that are not available in the public domain. Integrating such fragmented databases into one national portal will help overall assessment of the national soil resources and developing other knowledge resources, such as fertility maps for different soil nutrients at a finer scale. Once developed, such a database could be periodically updated with contribution from different organizations, such as ICAR Institutes, State Agricultural Universities, State Agricultural Departments, and International Organizations, *etc*. The present authors are aware that the above organizations collectively analyze a large number of soil samples per year from different parts of the country and it is only a matter of consensus to put them in a single national repository in the overall national interest. It is understandable that data querying from several disparate sources may give rise to the concern for the appropriate reconciliation of the soil test data. However, creating a national committee to oversee the data input, with particular reference to data sources and data quality could minimize such concerns. Developing a national portal of soil data will strongly fit into the current initiative of generating the "Soil Health Card" for millions of farm fields in the country. The geo-referenced soil analysis data from the "Soil Health Card" initiative could be stored in the national soil data repository and would be a logical starting point for a "national soil data repository" for the posterity. This will be an extremely valuable resource to help in research, planning and implementation of the improved agricultural practices at local, regional and country scale. From the nutrient mining standpoint, such a repository will help reorient fertilizer management practices based on agro-climate, soil type and management practices to minimize soil nutrient mining and sustain the soil fertility levels.

Conclusions

It is but obvious that the nutrient mining in agriculture cannot be avoided altogether. Indeed, different soils, under similar cropping systems and comparable management practices, will differ considerably in their inherent buffer powers to withstand the stress arising from "*nutrient mining*". In other words, the degree of soil vulnerability varies (Sanyal 2014). Multiple cropping systems and management practices adopted by farmers on numerous soil types in the country further complicate the nutrient mining scenario. Therefore, the allowable range of nutrient mining under variable climate-soil-crop-management domain needs to be assessed, at least at the regional scale. The current article discussed several research and application mechanisms that may provide some guidance to alleviate large-scale nutrient mining in the country. However, a larger objective of this article is probably to bring the nutrient mining issue in our collective consciousness as a threat to the quality of our soil resources and our food security. A national effort to address the nutrient mining may go a long way to maintain the quality of our soils for the posterity and to ensure the food security of the future generations.

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