Nutrient Mining: Addressing the Challenges to Soil Resources and Food Security

14

Kaushik Majumdar, Saroj Kumar Sanyal,
Sudarshan Kumar Dutta, T. Satyanarayana, and V.K. Singh

Abstract

Increasing population demands higher production and productivity of crops. Consequently, maintenance of soil fertility is a must for sustainable agriculture and future food security. Agriculturally productive soils have a pool of indigenous nutrients at any given point of time that are stored within the soil and may be available for supporting plant growth. This pool of nutrients, along with nutrient inputs from other sources such as irrigation water, crop residues, etc., constitutes the inherent soil nutrient-supplying capacity. There are several sinks of the native nutrients in the soil, most notably plant removal. Sustenance of inherent fertility of soils depends largely on replenishment of plant nutrients to the soil that are removed through intensive cultivation. *Nutrient mining* or negative balance between nutrient input and output results when the crop nutrient removal and nutrient losses to other sinks become higher than the soil-inherent nutrient supply. Current nutrient management strategies adopted by most farmers promote nutrient mining, as nutrient applications are inadequate and imbalanced. The application of 4R Nutrient Stewardship Principles, i.e., application of right source of fertilizer at right rate and time through a right method, has the potential to reduce nutrient mining

K. Majumdar
International Plant Nutrition Institute-South Asia,
Gurgaon 122 016, India
e-mail: kmajumdar@ipni.net

S.K. Sanyal
Former Vice Chancellor, Bidhan Chandra Krishi
Viswavidyalaya, Nadia 741 252, West Bengal, India
e-mail: sarojsanyal@yahoo.co.in

S.K. Dutta (✉)
International Plant Nutrition Institute-South Asia,
Kolkata 700 028, India
e-mail: SDutta@ipni.net

T. Satyanarayana
International Plant Nutrition Institute- South Asia,
Hyderabad 500 085, India
e-mail: tsatya@ipni.net

V.K. Singh
ICAR – Indian Institute of Farming System Research,
Modipuram, Meerut 250 110, Uttar Pradesh, India
e-mail: vkumarsingh_01@yahoo.com

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from soils. These core principles help manage nutrients in a manner that crop productivity is sustained or improved without soil fertility depletion, and farm production economics is improved while environmental impact of agricultural nutrients is minimized.

Keywords
Food security • Nutrient mining • Soil resources

14.1 Introduction

Sustainability is the overarching goal of intensive agriculture. It depends on how well we use our primary resources, such as land and water, to produce required crop yields while maintaining them for posterity. The capacity of the 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 is in the core of sustainability (SSSA 1995). The capacity of the soil to function adequately, in terms of producing enough food, depends on its ability to support plant growth. Soils, through a diverse chemical processes involving its organic and inorganic constituents, adsorb and release water and essential plant nutrients to support plant life. 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 sustained productivity of the soil.

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. A *negative* input–output balance of nutrients in the soil will eventually limit crop yield, facilitate *nutrient mining*, and result in the depletion of soil fertility. Experimental evidences suggest that restoring the fertility status of a soil denuded of its native fertility is a much costlier process that maintains the inherent fertility status through external application of nutrients. A soil severely depleted of its native potassium fertility status is difficult to restore even with external application due to structural collapse of its parent material (Sarkar et al. 2013, 2014). Rattan Lal (2014) in his recent paper quoted Sir Albert Howard who strongly believed in the relationship between the rise and fall of civilizations and their agricultural practices and argued that "the real arsenal of democracy is a fertile soil, the fresh produce of which is the birthright of nations." Indeed a fertile soil is a unique resource that ensures continued food and nutritional security of any nation, particularly so when population increases across the world are continuously challenging the boundary between food security and famine. The global population increase challenge will be intense in Asia, and particularly so in South Asia, due to the large base population of the region. Maintaining the soil resource base and its quality in a fertile state would be critical for sustained food security in the region.

14.2 Present and Future Nutrient Requirement for Food Production

With a projected increase of global population to 9.6 billion by 2050 from the current 7.2 billion, there is a tremendous need for increased production of food, feed, fuel, and raw materials from limited land area available for cultivation. India has around 18 % of the world population, 15 % of the world livestock with only 2.3 % of the total geographical area, and 0.5 % of pasture and grazing lands. The per capita availability of land has fallen drastically from 0.91 ha in 1951 to about 0.32 ha in 2001, and it is projected to decline further to 0.09 ha by 2050. The pressure on the land is increasing rapidly and land degradation is on the rise (Venkateswarlu and Prasad

2012). The current Indian population of 1.2 billion is expected to rise to 1.4 billion by 2025 and the country will need to produce at least 300 million tonnes (mt) of food grains for ensuring food security of the growing population. Ganesh-Kumar et al. (2012) summarized several studies that showed food grain demand in India reaching 293 mt by 2020 and increasing to 335 mt by 2026. Limited scope for horizontal expansion of cultivated area further accentuates the need for an increasing intensity of agricultural production. Greater crop yields per unit land area will require advances in genetics and crop improvement, increased fertilizer nutrient use, and improved soil and crop management technologies. Indeed Amarasinghe et al. (2008) estimated that the total calorie requirement (kcal/person/day) was 2495 in the year 2000 that is expected to increase to 2775 in 2025 and 3000 in 2050, respectively. Another study projected the food consumption levels in India to increase from the current level of 2400 kcal/per capita/day to about 3000 kcal/per capita/day in 2050 and estimated that the demand for cereals will rise to 243 mt in 2050 (Singh 2009). The major determinants for achieving future food security goals will be driven by the use of quality seeds, fertilizers, and water and its timely supply and application of modern technologies supporting precision management of resources.

Among the resources, fertilizer is one of the important inputs, whose judicious use would trigger the process of accelerated growth in production. Fertilizer use has played a significant role in the development of the agriculture sector in India, and the contribution of fertilizers to total grain production in India has increased from 1 % in 1950 to 58 % in 1995 (Subba Rao and Srivastava 1998). The total fertilizer nutrient consumption ($N + P_2O_5 + K_2O$) increased from 70 thousand tonnes in the early 1950s to 5.5 mt in 1980–1981, reaching an all-time high of 28.1 mt in 2010–2011 (FAI 2013). It is also estimated that there will be an additional demand for 40–45 mt of nutrients (NPK) along with the secondary and micronutrients by the year 2025 in order to meet the growing food production demand (Katyal 2001). Estimates based on the sufficiency approach showed that the requirement for zinc, iron, copper, boron, and manganese will be 324, 130, 11, 3.9, and 22 thousand tonnes by 2025 (Venkateswarlu and Prasad 2012).

14.3 Native Fertility and Inherent Soil Nutrient-Supplying Capacity

Janssen et al. (1990) defined inherent nutrient-supplying capacity or potential indigenous supply of nutrients from a soil as the cumulative amount of a nutrient originating from all indigenous sources that circulates through the soil solution surrounding the entire root system during one complete crop cycle. The native fertility or indigenous nutrient-supplying (INS) capacity of a soil at any given point of time is the nutrient pool that is stored within the soil and may be available for supporting plant growth. The INS by definition precludes inclusion of any nutrient contribution from external sources. However, it must be understood that the INS is not strictly confined to nutrients that are geogenic in nature, such as potassium, which has a potential source in micaceous minerals. Rather, the INS is a combination of geogenic and externally supplied nutrients that have been historically stored by the soil through various mechanisms such as adsorption, absorption, fixation, etc. Nutrient contributions from external sources may include irrigation water, atmospheric deposition, biological nitrogen fixation, and crop residues. In the absence of externally applied nutrient, INS provides support to plant growth by supplying the required nutrients. A soil with high indigenous supply of nutrients would be able to support adequate plant growth without external application, at least for a short period of time, while soils with low indigenous fertility will not be able to support plant growth without application of nutrients from external sources such as manures and fertilizers.

The INS is a critical component for estimating the amount of externally supplied nutrients required for supporting crops and cropping systems. Scientists and other stakeholders are in continued pursuit to critically estimate indigenous nutrient-supplying capacity of agricultural soils so that manure or fertilizer application could be optimized. The primary objective of the task is to supply adequate nutrition to the plants for effectively completing their life cycle. However, the co-benefits such as higher nutrient use efficiency, better economics of crop production, and less environmental footprint of agricultural nutrient use are substantial. The final outcome is a sustainable production system.

Soil testing is by far the classical method of estimating INS in a soil. Soil testing entails careful sampling of soil from the target location, extraction and analysis of available nutrients, and using the data through appropriate correlation and calibration to come up with a number that describes the quantity of a particular nutrient that will be available to the plants during a crop season. Several authors recently questioned the chemical methods adopted for analyzing available nutrients in the soil (Prasad 2013), the lack of correlation between soil test-based data for available nutrients and crop yield (Dobermann et al. 2002), or the approaches for developing integrated nutrient recommendations from soil test data (Tandon 2012). In fact, there are infrastructural issues that often limit the accuracy of INS estimates, particularly in Asia. For example, in the case of potassium, the NH_4OAc extract is the standard procedure followed in most soil testing laboratories. This method precludes the estimation of non-exchangeable potassium that contributes slowly to the soil available pool of potassium for plant uptake during the growing season. From a different perspective, the above method, employing the NH_4OAc extract of soil, does not provide any information about potassium depletion from the non-exchangeable pool in soil.

A plant-based approach for estimating indigenous nutrient-supplying capacity of soils was later developed by the International Rice Research Institute (Dobermaan et al. 2004). Instead of direct quantification of the nutrient status in the soil, this method relied on plant responses as an indicator of soil nutrient-supplying capacity. In this method, the yield of a crop in a field plot supplied with ample amounts of all limiting nutrients was compared with the yield of the crop in a plot that received all limiting nutrients except one that was omitted from the fertilization schedule. The difference in crop yield between the ample nutrient-supplied plot and the nutrient-omitted plot (yield loss) was ascribed to the direct effect of the omitted nutrient. This provided an indirect estimate of the indigenous nutrient-supplying capacity of the soil for the omitted nutrient. In other words, the crop is giving an indication of how much yield the soil can sustain in the absence of the external application of the omitted nutrient. For example, indigenous potassium supply (IKS) can be measured as total K accumulation in plant raised in a 0-K plot that received N, P, and all other limiting nutrients. The advantage of using plant indicators as nutrient supply is that they integrate nutrient supply from all the indigenous sources under field conditions (Dobermaan et al. 2004). A disadvantage of this approach is that the nutrient uptake is often affected by genotype and environmental variation in harvest index, and rooting pattern of the crop, which is often influenced by local growing conditions.

14.4 Nutrient Mining

The nutrient balance, the difference between nutrient input and output in a single crop growth period or in a cropping system cycle, is a critical determinant in the estimation of external nutrient application requirement. Several authors (Janssen et al. 1990; Witt et al. 1999; Witt and Dobermann 2004; Buresh et al. 2010) have used this approach as a major step toward development of site-specific nutrient management (SSNM) guidelines. Singh et al. (2014), in a recent paper, estimated the nutrient balance in a rice–wheat cropping system using the following equation:

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

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, crop residue, rainfall, and soil during the entire rice–wheat cropping cycle, respectively. The term "Eff" is the efficiency (%) of different nutrients from various pools of INS in terms of their availability to the crops. GY_r and GY_w are attainable grain yields (t ha^{-1}) of rice and wheat, respectively. RIE_{nr} and RIE_{nw} are the reciprocal internal efficiencies (kg plant nutrient per 1000 kg grain yield) for rice and wheat for N or P or K, respectively. It may be noted that the authors used the soil test values to evaluate the indigenous nutrient supply (INS) from soil during the cropping cycle. These indigenous nutrient contributions were obtained from the corresponding omission plot results in the approach used by Witt and Dobermann (2004) and Buresh et al. (2010). Singh et al. (2014) included the respective nutrient efficiency (Eff) values of the nutrients concerned as part of the equation to recognize that soil available nutrients have other sinks besides crop uptake.

In the above equation, nutrient (N, P, and K) contributions from soil available pool, irrigation water (IW), and rainfall (RF), crop residues (CR), and their availability (%, efficiency) to the crop constitute the INS or input part of calculation (the first part of the right-hand side of the equation). 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 several 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 aboveground crop biomass retained in the field after harvest and expressed in kg ha^{-1}. The second part of the right-hand side of the equation, crop yield multiplied by the corresponding reciprocal internal efficiency, constituted the crop removal (output) in the cropping system.

It is obvious from the above equation that a negative nutrient balance will result when the second part (crop removal) becomes higher than the first part (INS). This will lead to the depletion of soil native fertility, in other words "nutrient mining."

The reciprocal internal efficiency (RIE) is an important component in the nutrient balance equation as shown earlier. It has its origin in the modified QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model (Janssen et al. 1990; Witt et al. 1999) and is used to assess the nutrient removal by crops at different yield levels. For balanced nutrition, the QUEFTS model assumes a constant internal efficiency (of the major plant nutrients N, P, K) up to yield targets of nearly 70–80 % of the yield potential. In the QUEFTS model, two boundary lines described the minimum and maximum internal efficiencies (IEs, kg grain per kg nutrient in the aboveground plant biomass) of N, P, and K. For example, the minimum and maximum internal efficiencies for rice (*Oryza sativa* L.) 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) using on-farm data from over 2000 locations across a wide range of yields and nutrient status. The balanced N, P, and K uptake requirements for 1000 kg of rice grain yield were estimated from the above as being equivalent to 68.0 kg grain kg N^{-1}, 385 kg grain kg P^{-1}, and 69.0 kg grain kg K^{-1}, respectively, for the aforesaid linear phase (Dobermann and Witt 2004). Similarly, Chuan et al. (2013) also estimated minimum and maximum IEs for wheat (*Triticum aestivum* L.) as 28.8 and 62.6 kg grain kg N^{-1}, 98.9 and 487.4 kg grain kg P^{-1}, and 23.0 and 112.9 kg grain kg K^{-1}. 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. These authors also estimated the relationship between the grain yield and the nutrient uptake for suggesting the fertilizer application, avoiding excess or deficient nutrient supply.

The above section highlights the fact that the RIE used for calculating fertilizer requirement is significantly lower than the minimum IEs of the major plant nutrients for both the crops. Thus, the minimum internal nutrient efficiency for K for the cited case of rice cultivation was noted 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 was by about 40 % and 46 %.

Indeed, under such scenario, the point that comes up is if the 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), one of the envelopes of the internal nutrient efficiency curves, bound by the two boundary lines (describing the minimum and maximum IEs), would be used 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 overuse 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?

14.5 Mechanism of Nutrient Losses

The biggest contributor to nutrient mining is plant removal. Whenever the plant nutrient removal exceeds the combined nutrient inputs from indigenous sources and external application, the soil nutrient status gets depleted. This is a common occurrence in farmers' fields where suboptimal application of nutrients promotes nutrient mining in intensive cropping systems. The following table (Table 14.1) shows on-farm results across several locations and cropping systems that highlight the extent of nutrient mining in cultivators' fields.

The data in the above table highlight two very critical issues. The first is that potassium mining of different degrees is evident in all the locations and cropping systems, and potassium mining in most cases exceeds that of other nutrients. Generally no application of potassium by farmers or suboptimal K recommendation in the state recommendation promoted K mining. This is a common occurrence across India, mainly due to lack of awareness among the farmers and the common belief at the decision-making level that the Indian soils are rich in potassium and may not need external application to support adequate crop growth. The second issue highlighted by the above table is the difference in crop removal in the SR and SR + M treatment. The N, P, and K application rates are similar in both the treatments, but the SR + M treatment received application of deficient secondary and micronutrients. The results showed that addition of secondary and micronutrients to SR triggered higher removal of major nutrients in the on-farm trials. Application of limiting secondary and micronutrients, even under suboptimal application of major nutrients, may increase crop yield, leading to higher yields and hence *more mining* of major nutrients (Table 14.1).

Nutrient mining may also arise from other processes such as volatilization or leaching losses as well as soil erosion. For example, nitrogen (N) is highly mobile in the soil and has high probability to be lost from the soil system through volatilization and leaching. On a global scale, at least 50 % of the fertilizer N applied is lost from the agricultural systems (Ladha et al. 2005). Nitrogen can be lost from agricultural systems as ammonia, nitrous oxide (N_20), or nitrogen oxides (NOx). Sharma et al. (2008) summarized the results of N_2O emission from agricultural soils based on actual field measurements. These experiments reveal average N_2O–N emission of 0.0025 and 0.0055 kg kg^{-1} N applied from rice and wheat fields, respectively. Nitrogen oxide (NOx)

Table 14.1 Nutrient use and removal at cultivators' field in India

Cropping system/location	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, UP (24)	FFP	206	28.4	0.0	133	22	150	73	6.4	−150
	SR	220	48.0	74.7	186	35	160	34	13	−85.3
	SR + M	220	48.0	74.7	204	40	174	16	8	−99.3
Rice–rice/Warangal, AP (24)	FFP	298	60.3	70.6	168	47	172	130	13.3	−101.5
	SR	240	52.4	66.4	185	52	189	55	0.4	−135.6
	SR + M	240	52.4	66.4	199	56	202	41	−3.6	−135.6
Pearl millet–mustard/ Deesa, Gujarat (18)	FFP	114	37.1	0.0	171	45	104	−57	−7.9	−104
	SR	130	39.3	54.0	193	51	116	−63	−11.7	−62.1
	SR + M	130	39.3	54.0	200	54	122	−70	−14.7	−65.1
Pearl millet–wheat/ Thasra, Gujarat (18)	FFP	130	34.9	0.0	129	28	65	1	6.9	−65
	SR	200	43.7	83.0	194	43	95	6	0.7	−12
	SR + M	200	43.7	83.0	200	44	101	0	−0.3	−18
Maize–Bengal gram/ Gadag, Karnataka (24)	FFP	80	38.0	0.0	138	26	133	−58	12	−133
	SR	110	32.8	20.8	142	28	169	−32	4.8	−148.3
	SR + M	110	32.8	20.8	156	32	181	−46	0.8	−160.3
Rice–green gram/ Kakdwip, WB (18)	FFP	52.5	26.6	34.0	130	22	129	−77.5	4.6	−95
	SR	100	34.9	66.4	138	26	161	−38	8.9	−94.6
	SR + M	100	34.9	66.4	148	29	176	−48	5.9	−109.6
Maize–wheat/Kangra, HP (18)	FFP	50	14.0	21.6	678	17	53	−18	−30	−31.4
	SR	170	37.6	58.1	130	30	89	40	7.6	−30.9
	SR + M	170	37.6	58.1	135	33	97	35	4.6	−38.9
Cotton–pearl millet/ Deesa, Gujarat (18)	FFP	202	37.8	0.0	287	46	85	−85	−8.2	−85
	SR	320	43.7	83.0	324	52	91	−4	−8.3	−8
	SR + M	320	43.7	83.0	378	53	102	−58	−9.3	−19

Source: AICRP-IFS Reports (2011–12); *FFP* farmers' fertilizer practice, *SR* state recommendation, *SR + M* state recommendation + micro- and secondary nutrients

emission from soils is primarily a result of NO production by the microbial oxidation of ammonium, the process being known as nitrification. The NO production in the soils also occurs through microbial reduction of nitrate (denitrification). Estimates (Sharma et al. 2008) suggest that about 0.5 % of fertilizer N applied to agricultural fields was emitted to the atmosphere as NO. Application of fertilizers in the agriculture fields and the livestock population is mainly responsible for NH_3 emission. Although most emissions of ammonia are from manure or natural sources, experiments demonstrate that nitrogen losses to the atmosphere in the form of ammonia following the application of urea can amount to 20 % or more, under temperate conditions. Losses occur when the urea is not incorporated into the soil immediately after spreading, and they are particularly high in calcareous soils. Losses are even higher, up to 40 % or more, under tropical conditions, for flooded rice and perennial crops to which the urea is applied on the soil surface, such as banana, sugar cane, oil palm, and rubber. Some studies have shown leaching loss of N from soils in the Indo-Gangetic Plains (IGP) as 10–15 kg N ha^{-1}, while ammonia volatilization loss is 20–30 kg N ha^{-1} with application of 120 kg N ha^{-1} in rice and wheat (Majumdar et al. 2014a). The Indian soils, being in the subtropical region coupled with preponderance of tillage practices, are rarely sufficient in nitrogen. The volatilization and leaching losses of N aggravate the situation. These losses constitute removal of nutrients from the soil available pools, in other words nutrient mining, and crop production relies more on adequate external application of N

Table 14.2 Effect of slope gradient on loss of available phosphorus from different tilled soil management treatments

	Loss of P in runoff			Loss of P in erosion		
Slope gradient	Bare fallow	Maize–maize	Maize–maize (mulch)	Bare fallow	Maize–maize	Maize–maize (mulch)
%	Kg ha^{-1} yr^{-1}					
1	3.61	0.58	0.0	1.97	0.26	<0.1
5	3.41	1.49	0.03	9.30	1.03	<0.1
10	3.72	0.62	1.0	20.25	0.87	<0.1
15	4.68	1.70	0.93	13.08	2.29	<0.1

through fertilizer/manure sources rather than on the native soil reserve of nitrogen.

Phosphorus (P) and potassium (K), on the other hand, have lower potential for loss from the soil than N. Except erosion (for P) and leaching (for K), the extent of loss by other means is negligible for these two nutrients. Under favorable growth conditions, most agricultural crops recover 20–30 % of the applied phosphorus depending upon the growth stage of P applications. A large portion of the unused P accumulates in the soil as the soil–fertilizer reaction products, and eventually a part of it is recovered by subsequent crops over time; a much smaller fraction of P is lost as runoff (both particulate and dissolved P) or through leaching that can cause secondary off-site impacts. All forms of P within the soil system are subjected to a variety of pathways of transport at the soil profile, hill slope, or catchment scale. Particulate and colloid P transport is most commonly associated with soil erosion, which arises from raindrop impact and overland flow. Additionally, when fertilizer or manure application is coincident with fast or energetic water flows, this will contribute to particularly high losses (Gburek et al. 2005). Singh and Lal (2005) stated that principal mechanism of P loss from soil is by erosion as P-enriched sediments. The authors showed (Table 14.2) that the loss of P in erosion is higher in plowed bare or continuous maize treatments compared to maize crop with mulch. Further, the loss of P increased with increase in slope gradient from 1 % to 15 % in plowed and bare treatments.

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 provides an abundant in situ source of this nutrient. Besides, potassium gets absorbed in the negatively charged interlayer space of soil clays, a process that prevents its loss from the soil and maintains the nutrient in available form for plant uptake. However, on the issue of nutrient mining, potassium is probably the most pertinent nutrient that has the potential of significantly affecting agricultural production in the country. Potassium input–output budgets in agriculture are nearly always highly negative. Estimates for India and Indonesia suggest annual K losses of about 20–40 kg K/ha that have been increasing steadily during the past 40 years (Majumdar et al. 2014a). Historically low application rates of potassium in crops have led to overdependence on the native soil reserve of potassium. Besides crop removal, substantial amount of soil K (and other basic cations) could be lost via leaching in fields with adequate drainage. Leaching losses of K can be substantial in highly permeable soils with low cation exchange capacities. Yadvinder-Singh et al. (2005a) found that leaching losses of K were 22 % and 16 % of the applied K, respectively, in sandy loam and loamy soils maintained at submerged moisture regimes. For Bangladesh, such losses can be as high as 0.1–0.2 kg K ha^{-1} d^{-1} (Timsina and Connor 2001).

14.6 Soil Organic Carbon Dynamics and Nutrient Mining

Carbon sequestration, the storage of carbon in soil organic matter, is a crucial process for mitigating global warming and climate change. Balanced and adequate nutrient management has been identified as crucial to soil organic C (SOC) sequestration in tropical soils (Bhattacharyya et al. 2007; Mandal et al. 2007). Several studies cited by Pathak et al. (2010) stated that adequate supply of nutrients in soil could enhance biomass production and SOC content in the soil and enhance crop productivity. Although SOC sequestration is a major challenge in soils of the tropics and subtropics, the authors (Pathak et al 2010), while analyzing data from 26 long-term fertilizer experiments in India, showed that the application of balanced fertilizer rates along with farmyard manure has good potential in C sequestration in Indian soils and mitigating GHG emission without any additional cost. Rather, it increased yield and net return in majority of the experiments. Increase in SOC in soil makes it more productive leading to increase crop yield. Majumder et al. (2008) also observed that balanced fertilization caused a net enrichment of both the total carbon and organic carbon content of the soils in rice–wheat–jute rotation because of a large amount of crop residues and root biomass C left over in the soil owing to the significantly higher yield of the crops grown under those treatments compared to the control.

The current authors believe that there is a distinct connection between carbon sequestration and nutrient mining. During the C sequestration process, plant nutrients present in the organic substrate are immobilized in the complex organic structure of the sequestered carbon. Once immobilized within the SOC, nutrients are not available to plants or are not prone to be lost from the soil by other mechanisms as stated in the previous section. However, as the organic carbon in the soil gets decomposed, the nutrients within the organic matter become available for plant uptake or loss. Mineralization and immobilization of nutrients in the soil are critical processes influencing the dynamics of nutrients within the soil system. Both the processes are biochemical in nature and are bound to the activities of the heterotrophic biomass. These two processes significantly influence the dynamics of several nutrients, namely, N, P, S, and the micronutrients in soil–plant system. Indeed, the process of mineralization is responsible for the fundamental transformation of organic nutrients in plant residues back into the simple inorganic forms originally used by plants in their metabolic activities (Sanyal et al. 2009a).

In the current context, importance of carbon (chiefly organic) sequestration in soil and co-sequestration of plant nutrients are of importance in the soil nutrient mining. It is apparent that the breakdown of soil organic matter (SoM) under the different land use pattern would adversely affect the soil's capacity to store the inorganic nutrients, thereby protecting them from several avenues of loss. In other words, such depletion of SoM will encourage the nutrient mining. The subtropical climate in India aggravates loss of carbon from soil. Besides, heavy tillage before growing crops also exposes soil organic matter and mineralization rates are high. Saha et al. (2011) suggested that the most significant factors affecting SOC pools in a watershed include land use, land use changes, and soil erosion. The authors quoted several studies that showed cultivation can reduce SOC storage and may promote erosion loss of SOC.

Hence, attempts to sequester the organic matter in soil will help reduce the deleterious effect (on soil fertility) associated with nutrient mining in Indian agriculture. The information on such correlations is worth looking for as to how the relevant soil management options (including the incorporation of the inorganics and reduced tillage) can best be related to such nutrient dynamics in soil under a crop. Indeed, the beneficial effects of carbon sequestration in soil, including the carbon credit and budgeting, will be greatly reinforced in case the former is noted to cause significant retention of the inorganic nutrients in soil matrix, thereby preventing them from being lost.

14.7 Current Situation of Nutrient Mining

Assessment of nutrient mining through estimating nutrient balances using information on nutrient additions and removals generates useful, practical information on whether the nutrient status of a soil (or area) is being maintained, built up, or depleted. Estimates of nutrient input and output, as discussed in the previous section, allow the calculation of nutrient balance sheets for both individual fields and geographical regions. Nutrient balance sheets calculated in most soils of India have shown the signs of nutrient mining as crop nutrient removal far exceeded the nutrient additions through manures and fertilizers. During 1999–2000, the crop removal of nutrients is estimated to be about 28 mt, while the fertilizer consumption was only 18 mt with an annual nutrient gap of 10 mt. Although a part of this nutrient gap is expected to be bridged from sources like organic manures and through biological processes, still there remains a distinct gap in nutrient removal and supply leading to nutrient mining from the native soil which, in turn, poses a serious threat to long-term sustainability of crop production (Hegde and Babu 2001). Tandon (2004) also estimated the deficit between removals and additions at 8–10 M t N + P_2O_5 + K_2O per year and reported this trend to continue in the future (see later).

In India, the state-wise approaches to crop nutrient balances have been developed in 2001 considering the nutrient additions and removal data either from 1998 to 1999 or 1999 to 2000. Since then, the information on nutrient balances has not been updated. Satyanarayana and Tewatia (2009) made an attempt to generate fresh information on nutrient balances in major agriculturally important states of India considering the information available from FAI (2008). Nutrient-balance calculations in most of the cases do not give real picture as they consider nutrient removal by crops and addition through fertilizers neglecting contribution from sources other than fertilizers such as organic manures, crop residues and stubbles, irrigation water, etc. However, in this paper, the authors have tried to overcome that limitation by considering nutrient additions through organic sources wherever possible from the information available in the published literature.

While calculating nutrient removal by crops at the present production levels, attempt was made to consider removal of nutrients by fruits and vegetables in all the states; tea, coffee, jute, rubber, and other plantation crops in states wherever applicable and the total production values have been multiplied with the nutrient uptake per tonne of produce and arrived at removal figures. While generating data for nutrient additions, apart from additions through fertilizers, nutrient contribution from other sources like organic manures, farmyard manure, crop residues, irrigation water, biological nitrogen fixation, etc. has also been considered for some of the states depending upon the availability of information. Where information is not available, nutrient additions through only fertilizer are considered. Similarly, wherever nutrient balance studies were well established by previous authors, efficiency factors were involved for calculating net nutrient balances.

The above study (Satyanarayana and Tewatia 2009) revealed that the nutrient use pattern in majority of the agriculturally important states of India is inadequate and mostly dominated by NP fertilization. The overall N balance seemed to be positive in India (Table 14.3), with highest positive N balance observed in the northern region, which could be attributed to significant addition of nutrients through both inorganic and organic sources. The overall P balance seemed to be negative due to an excessive mining of P to an extent of 4.2 mt observed in the western region. The mining of K is evident in almost all the states, which implied neglect in the use of K fertilizers. Potassium mining in India was estimated at 9.7 mt, and the highest K mining was noticed in the western region (−3.8 mt), followed by northern, southern, and eastern region, respectively. Dutta et al. (2013) estimated K input–output balances in different states of India using the IPNI NuGIS approach and reported negative K balances in most of the states suggesting deficit K application as compared to crop K uptake, contributing to mining of native K. The authors included the manure application, along with the potassic fertilizers, across the different states of India to capture the most recent K balance scenario in India (Fig. 14.1).

It is evident from the figure that K_2O depletion was more in 2011 than in 2007 in most of the

Table 14.3 Region-wise nutrient additions, removal by crops, and apparent balances in India. All units in '000 t

Region	Nutrient	Addition	Removal	Balance
East	N	2079	1733	346
	P_2O_5	794.6	782.4	12.2
	K_2O	517.6	2428.2	−1910.6
	NPK total	3391.1	4943.7	−1552.6
West	N	3955.6	3838.5	117.1
	P_2O_5	1797.5	2212.3	−414.8
	K_2O	756.7	4579	−3822.3
	NPK total	6510	10,630	−4120
Northern region	N	5016.8	2728.3	2288.5
	P_2O_5	1432.6	1258.4	174.2
	K_2O	918.1	3534	−2615.9
	NPK total	7367.5	7520.7	−153.2
Southern region	N	2212.9	1755.1	457.8
	P_2O_5	844.7	836.4	8.3
	K_2O	1118.1	2447.7	−1329.6
	NPK total	4175.8	5039.1	−863.3
India	N	13264.3	10054.9	3209.4
	P_2O_5	4869.4	5089.5	−220.1
	K_2O	3310.5	12988.9	−9678.4
	NPK total	21444.4	28133.5	−6689.1

northern (such as Punjab, Haryana, Uttar Pradesh), eastern (Assam, Bihar, Orissa, Jharkhand, and Chhattisgarh), and western (such as Gujarat, Rajasthan) states of India. This indicated that soils in these states typically received less than the required amount of K_2O. The states of West Bengal and Tamil Nadu showed positive K_2O balances in both 2007 and 2011, suggesting that no K mining has occurred in these two states. Indeed the negative K_2O balance for several states in the country, such as Uttar Pradesh, Punjab, Haryana, Rajasthan, and Madhya Pradesh, increased significantly during the period from 2007 to 2011, probably due to lesser fertilizer application and/or higher crop production per unit land holding. However, such changes in native soil K fertility under intensive cropping can also be quite abrupt, particularly when the vegetables are included in the rice-based cropping systems (Sanyal et al. 2009a). Sen et al. (2008), while assessing the changes in nutrient availability through the GIS-based fertility mapping, observed the K fertility in an intensively cultivated village in the alluvial zone of West Bengal to decrease perceptibly within 2 years. The range of available K_2O changed from 87–448 kg ha^{-1} in 2006 to 56–375 kg ha^{-1} in 2008 with the mean value declining from 166 kg ha^{-1} in 2006 to 88 kg ha^{-1} in 2008. Potassium fertility of the village was generally low to medium in 2006, but the frequency distribution shifted more toward the low fertility category with a substantial increase in sample number in the lowest category (Fig. 14.2). These authors noted that the lower application of K during this period due to unavailability of K fertilizers and high K uptake by the vegetable crops apparently contributed to this sharp decline in K fertility of soils over such a short period of time.

Potassium additions through the prevailing practices of manuring and residue recycling, as well as the meager inputs through K fertilizers, are not sufficient to match the K removal by different crops, and therefore, tremendous efforts are needed to promote K consumption through use of K-rich fertilizers.

The current trends of nutrient balances reveals that the gap between nutrient use and supply in

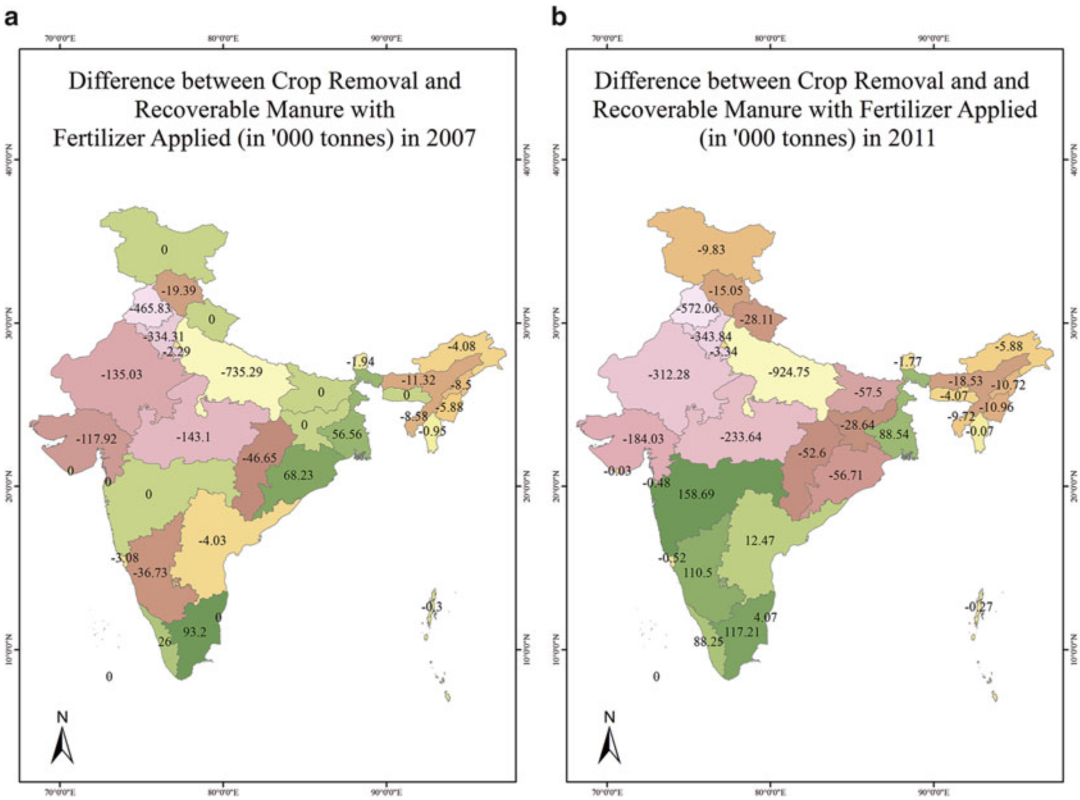

Fig. 14.1 The K_2O (applied fertilizer + manure – crop removal) balance for (**a**) 2007 and (**b**) 2011 across different states of India (Source: Dutta et al. 2013)

farming areas will continue to grow wide on account of intensive cropping, and therefore, there is a need to ensure proper and timely supply of major as well as secondary and micronutrients. Other than additions through fertilizer nutrients, practices like recycling of crop residues, rather than removing the residues from the field, and the use of animal manures through appropriate composting processes should be encouraged in place of diverting these resources for fuel and other secondary purposes.

Table 14.4 gives an example of the ground reality in the context of nutrient mining in the Murshidabad district of West Bengal as a case study (Sanyal et al. 2009b). Thus, taking only rice, wheat, mustard, and jute as the growing crops in the said district, and utilizing the state-recommended nutrient application rates and the ratio, this study demonstrated the deficit of N, P_2O_5, and K_2O running into 19,423 t, 10,669 t, and 11,438 t, respectively (Table 14.4). However, in Murshidabad, agriculture is much diversified. If one includes all other crops in such calculation, for example, 53,000 ha of pulses, more than 20,000 ha under fruits, and nearly 86,000 ha under different vegetables, a scenario of huge deficit of nutrients will show up. This deficit, however, is not confined to NPK alone: the corresponding levels of the secondary and the micronutrient deficits do also cause significant production loss. The calculation in the table was based on 100 % acceptance of the state recommendation, which is rarely the case at the ground level. This suggests that the total consumption of the district is being distributed among all the crops, fostering suboptimal nutrient application to most of them encouraging *nutrient mining* from soil to an unaccounted and alarming proportion.

Further, if the average use efficiency of fertilizers (N 50–60 %; P 15–25 %, K 60–70 %)

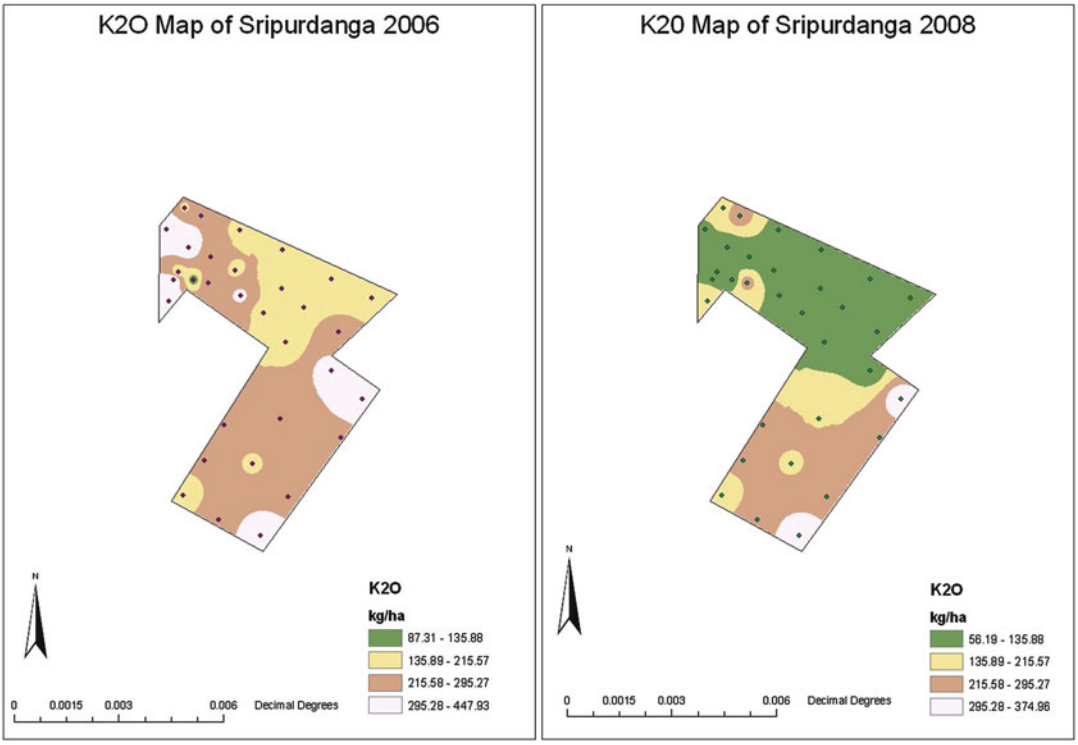

Fig. 14.2 Comparative maps of available potassium before and after four cropping seasons (Source: Sen et al. 2008)

Table 14.4 Theoretical consumption of nutrients at the state-recommended level in Murshidabad, West Bengal

Crop	Area (ha)	State recommendation (kg/ha)			Consumption at 100 % acceptance of state recommendation (t)		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
Rice	406,724	60	30	30	24,403	12,202	12,202
Mustard	62,031	80	40	40	4962	2481	2481
Wheat	133,961	120	60	60	16,075	8038	8038
Jute	143,852	50	25	25	7193	3596	3596
Calculated nutrient requirement for four crops at state-recommended fertilizer rates					52,633	26,317	26,317
Actual fertilizer consumption in the district					33,210	15,648	14,879
Difference					−19,423	−10,669	−11,438

is taken into account, the nutrient addition through fertilizers is further reduced, and therefore, the removal exceeds the consumption and the nutrient gap is widened. Nevertheless, the situation is balanced by addition of the nutrients through biofertilizers, FYM, compost, green manuring, or addition of crop residues in the field. The consumption data on secondary and micronutrient fertilizers are not available. There is a need to compute nutrient balances with respect to secondary and micronutrients, giving emphasis primarily to the most limiting nutrients like S, Zn, and B.

With the intensively grown production systems of India, heavy removal and inadequate replenishment of nutrients resulted in multiple nutrient deficiencies and depletion of soil nutrient reserves. For sustaining the crop productivity

Table 14.5 Initial soil K status, K addition, K removal, and subsequent K balance

Treatments	Initial soil K (kg/ha)	K added through fertilizer (kg/ha)	Total K removal (kg/ha)	K balance (kg/ha)	Postharvest soil K (kg/ha)
Kharif groundnut, Bhubaneswar site 1 (replicated trial)					
BFT (NPKSZnBCa)	113	60	28.3	144.7	98.5
RDF	113	40	27.4	125.6	74.6
FFP	113	57	26.2	143.8	70.5
Kharif groundnut, Deoda, Dharmasala site 2 (non-replicated trial, $n = 1$)					
BFT (NPKSZnBCa)	147	60	19.0	188	103.3
RDF	147	40	18.4	168.6	80.2
FFP	147	57	15.4	188.6	119
Rabi groundnut, Bhubaneswar site 3 (replicated trial)					
BFT (NPKSZnBCa)	127	60	46.1	140.9	110.3
RDF	127	40	34.4	132.6	110.7
FFP	127	57	38.6	145.4	80.6
Rabi groundnut, Sankaradiha and Bhuban, Dharmasala site 4 (non-replicated trial, $n = 7$)					
BFT (NPKSZnBCa)	104.4	60	49.1	115.3	158.7
RDF	104.4	40	41.6	102.8	143.1
FFP	104.4	57	30.0	131.4	105.4

and to restore the soil fertility, there is a need to arrest depletion of soil nutrient reserves. Indeed, tremendous efforts are needed to promote the right use of plant nutrients through promoting the concept of 4R Nutrient Stewardship (IPNI 2012).

As stated above, Tandon (2004) studied the nationwide scenario of nutrient balance and reported an annual mining of 9.7 M t of NPK (19 % N, 12 % P, and 69 % K) from the soil. He attributed higher K mining to higher crop removal, which is, on an average, 1.5 times greater than N, while K application through fertilizer is much lower than that of N or P.

14.8 Challenges for Nutrient Mining

If any plant nutrient, whether a major, secondary, or a micronutrient, is deficient in the soil, then crop growth is likely to be affected and nutrient mining would be promoted. Majumdar et al. (2014a) categorized the nutrient management approaches prevalent in the country and adopted by farmers into the following three groups based on their order of acceptance:

- Farmer applying fertilizer according to their own perception
- Ad hoc fertilizer recommendation
- Soil test-based fertilizer recommendation

According to the authors, 70–80 % of farmers, involved mainly in field crop production, apply fertilizer based on their own perception or as advised by their progressive peers. This has promoted over- or underuse of fertilizer, large-scale imbalance in nutrient application, and improper timing of fertilizer application. Scientists and policy makers have pointed out the declining nutrient use efficiency/fertilizer response, farm profitability, as well as sharp increase in areas with multiple nutrient deficiencies as clear indicators of inappropriate fertilization approaches adopted by farmers. The application of nitrogen 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.

P and K use is low as compared to N, and secondary and micronutrients are generally omitted from fertilization schedule, leading to possibility of nutrient mining. Such practices promote large-scale mining of nutrients that are under-applied.

Traditionally balanced fertilization in India means use of N, P_2O_5, and K_2O in a certain ratio, ideally 4:2:1, on a gross basis both in respect of areas and crops. Whatever may be the origin of 4:2:1 ratio, farmers in India do not follow it under most circumstances (Majumdar et al. 2014a). The ad hoc recommendations, developed by different state governments, are based on crop responses over large areas and provide recommendations for medium fertility soils. The recommendations are prescribed for large areas and do not take into account the spatial and temporal variability in soil nutrient-supplying capacity. This often results in over- or under-fertilization leading to yield and economic losses. Besides, the recommendations are generally for medium yield targets and often fall short for higher yield targets achievable through the use of better seeds and good management. In the case of soil test-based recommendations, only available nutrient levels are measured and used as basis for the recommendation. This may not affect the N recommendations as Indian soils are traditionally poor in available N and recommendations are not based on residual N in the soils. However, in the case of potassium, using only available or exchangeable K as the driver of fertilizer recommendation may lead to the depletion of non-exchangeable K. Presence of mica and feldspar in soils provides an in situ source of this nutrient that maintains the exchangeable fractions at the cost of depletion of non-changeable form.

With the realization of the lacunae in the current nutrient management approaches, the site-specific nutrient management (SSNM) strategies (Majumdar et al. 2014a) are now being advocated. SSNM strategies ensure 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 agroecologies (Singh et al. 2014). The in-built algorithms of SSNM cut down over- and underuse of fertilizers and significantly reduce the probability of nutrient mining. Therefore, 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.

14.9 Fertilizer Best Management Practices for Nutrient Mining

Fertilizer best management practices (FBMPs) are agricultural production techniques and practices developed through scientific researches and verified in farmers' fields to maximize economic, social, and environmental benefits (Majumdar et al. 2014b). FBMP is aimed at managing the flow of nutrients in the course of producing affordable and healthy food in a sustainable manner that protect the environment and conserve natural resources at the same time profitable to producers.

The 4R Nutrient Stewardship approach, evolving from the conceptual framework of FBMPs, is an essential tool in the development of sustainable agricultural systems because its application can have multiple positive impacts. The basic principle behind fertilizer best management practices is simple, that is, the "4R" – using the right fertilizer source, at the right rate, right time, and right place which conveys how fertilizer applications can be managed to achieve economic, social, and environmental goals.

Application of 4R strategies to nutrient management in crops has the potential to reduce nutrient mining from soil. The following section provides examples of application of the 4R strategies in crops and cropping systems to reduce nutrient losses from the soil.

14.9.1 Right Source and Nutrient Mining

The form of added N plays a role in regulating N losses and influencing NUE. Nitrogen fertilizers predominantly contain N in the form of ammonia, NO_3^-, or urea. Among these forms, NO_3^- is the most susceptible to leaching, ammonia the least, and urea moderately susceptible. Ammonia and urea are more susceptible to volatilization loss of N than fertilizers containing NO_3^- (Ladha et al. 2005). Controlled release compounds have the potential to reduce losses of N from the system. A recent study (Halvorson and Del-Grosso 2012) commonly used granular urea (46 % N), liquid UAN (32 % N), a controlled-release polymer-coated urea (ESN®), stabilized urea and UAN products containing nitrification and urease inhibitors (SuperU and UAN + AgrotainPlus®), and a subsurface band ESN treatment (ESNssb) in maize and showed that the right choice of nitrogenous fertilizer significantly reduced N loss in irrigated maize (Fig. 14.3).

Singh et al. (2002) studied the effect of different sources of N on distribution and depletion of K in a rice–wheat cropping system grown on a vertisol for 8 years. The study revealed that continuous growing of rice–wheat for 8 years without FYM or green manure (GM) as a source of N caused a decline in the exchangeable K from 19.5 mg K 100 g^{-1} soil (initial) to 16.0 and 13.8 mg K 100 g^{-1} soil in the control and 90 kg N ha^{-1} treatments, respectively. However, the use of either FYM or GM together with 90 kg N ha^{-1} favored a buildup of solution and exchangeable K (Table 14.6). Application of FYM or GM alone as a source of N did not have a significant effect on exchangeable K. Depletion of K, which was measured as the difference of initial and final HNO_3 + $HClO_4$-K (after 8 years), led to a significant depletion of HNO_3 + $HClO_4$-extractable K (non-exchangeable) in the presence or absence of FYM or GM indicating a greater release of K to available pool. The magnitude of depletion was larger at 180 kg N ha^{-1}. The study indicated that choosing a right source of N resulted in better available K and the increase in the exchangeable K in the presence of FYM or GM as a source of N could be due to an increase in the exchange sites (CEC) as a result of addition of manure.

14.9.2 Right Rate and Nutrient Mining

Application of right fertilizer rate ensures balanced supply of plant nutrients with better crop uptake and minimal losses. Mohapatra et al. (2013) studied the response of groundnut to balanced fertilizer application and compared different rates of fertilizer application, namely, balanced fertilizer rate based on soil testing (BFT), state fertilizer recommendation (RDF), and farmer fertilizer practice (FFP). BFT varied across different locations involving variable rates of NPKSZnBCa, while RDF (only fixed rates of NPKSZnBCa) and FFP (fixed rates of NPK only) treatments were the same at all the experimental sites. The results revealed that the BFT recorded significantly higher pod yield of groundnut than any of the other treatments used across all locations and seasons and the average yield of groundnut with BFT was 2226 kg/ha followed by RDF (1885 kg/ha) and FFP (1611 kg/ha), respectively. The study indicated that choosing right fertilizer rate resulted in better groundnut yield while reducing the extent of K mining from soil (Table 14.5). With an average initial soil K status of 123 kg/ha, the average K balances after harvest of groundnut in BFT, RDF, and FFP treatments were 147.2, 132.4, and 152.3 kg/ha, respectively. However, the average postharvest soil K status in BFT, RDF, and FFP treatments was 117.7, 102.1, and 93.9 kg/ha, respectively. This indicated a corresponding K mining of 5.3, 20.9, and 29.1 kg/ha, respectively.

Singh et al. (2013) have also shown that not applying the right rate of potassium could cause nutrient mining in soils under intensive cropping system. Soil properties before the rice crop and after the wheat crop were used to determine change during one rice–wheat cropping cycle

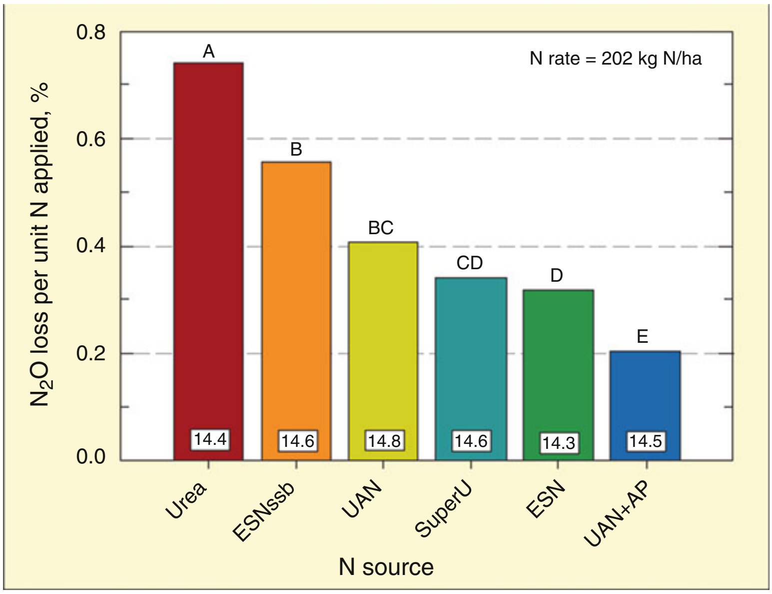

Fig. 14.3 Growing season soil nitrous oxide (NO) loss per unit of N applied as a function of N fertilizer source averaged over strip-till and no-till irrigated corn production systems in 2009 and 2010 near Fort Collins, Colorado. Average grain yields (t/ha) are shown in a *white box* within each bar

Table 14.6 Distribution of different forms of K as influenced by the use of different sources of N after 8 years of a rice–wheat system grown on a vertisol

Treatment	Water-soluble K (mg/100 g soil)	NH_4OAc–K (mg/100 g soil)	$HNO_3 + HClO_4$–K (mg/100 g soil)	Depletion of K (mg/100 g soil)
Initial	3.1 ± 0.2	19.5 ± 3.1	303 ± 8.2	–
Control	2.5	16	293	10
90 kg N ha^{-1}	3.2	13.8	289	13.5
180 kg N ha^{-1}	3.2	12.5	285	17.5
90 kg N + FYM 5 t ha^{-1}	4	23	288	15
90 kg N + GM 6 t ha^{-1}	4.1	24	288	14.1
5 t FYM ha^{-1}	3	21	296	6.5
6 t GM ha^{-1}	2.8	20.5	298	4.5
CD (P = 0.05)	0.4	1.1	9.7	–

(Table 14.7). In the absence of added K, exchangeable K decreased by 6–9 mg kg^{-1} and non-exchangeable K decreased by 18–30 mg kg^{-1} during one rice–wheat cropping cycle. With application of K, exchangeable K increased by 6–9 mg kg^{-1} and non-exchangeable K increased by 7–14 mg kg^{-1}. The difference between application of K and the farmer's practice without the added K after one rice–wheat cropping cycle ranged from 13–18 mg kg^{-1} for exchangeable K and 26–41 mg kg^{-1} for non-exchangeable K across the locations (Table 14.7). The decline in soil K without added K (Table 14.7) highlights the risk of rapid short-term mining of soil K with the farmer's current practice of using relatively high rates of N and P with little or no use of K. Long-term cropping with negative K balances has been associated with yield declines in the rice–wheat system in South Asia (Bijay-Singh et al. 2003). Although the K-supplying capacity of illite-dominated alluvial soils of the Indo-Gangetic Plains in India is relatively high, long-term intensive cropping with inadequate application of K can result in K mining leading to large negative balances and depletion of native K reserves (Yadvinder-Singh et al. 2005b).

Table 14.7 Change in soil potassium (K) during one cycle of rice–wheat cropping at five locations in northern India. The K × M × location interaction was not significant at $P \leq 0.05$ for all the listed parameters

Parameter	Fatehgarh Sahib	Meerut	Banda	Barabanki	Bhagalpur
Change in exchangeable K (mg kg^{-1})					
No K	−6	−6	−7	−8	−9
+K	6	7	7	8	9
Difference[a]	13***	13***	14***	17***	18***
Change in non-exchangeable K (mg kg^{-1})					
No K	−30	−22	−19	−26	−18
+K	11	9	7	14	14
Difference	41***	31***	26***	40***	33**

ns = not significant at $P \leq 0.05$, * = significant at $P \leq 0.05$, ** = significant at $P \leq 0.01$, and *** = significant at $P \leq 0.001$

[a]Difference between non-rounded means for two no-K treatments (no application of K, S, or Zn and application of S + Zn) and two + K treatments (application of K only and application of K with S + Zn)

14.9.3 Right Time and Nutrient Mining

Assessing crop uptake dynamics and patterns can be an important component in determining appropriate timing of nutrient application. Applications timed and targeted at specific growth stages may be beneficial to crop yield and/or quality in some production systems for some nutrients, most notably N. Timed and targeted applications may also be beneficial to reduce environmental impacts of nutrient loss from soil. The basic objective is to optimize the congruence of supply and demand of N (Giller et al. 2004). Inappropriate time of fertilizer application does not allow the plants to take up the nutrients from the soil, and the unutilized nutrients in the soil increases the probability of loss. Besides matching the physiological demand stages of crops, a rate X time combination becomes a major factor in reducing nutrient loss from the soil in on-farm situations. For example, fertilizer nutrient rates are generally decided before the cropping season, based on anticipated yield and soil nutrient-supplying capacity. In the case of nitrogen application in major cereals, the quantity of total N to be applied is generally split into 2–3 applications matching the physiological demand stages of the crop concerned. However, any in-season changes in climate, pest, disease attacks, etc. may change the yield targets and crop nutrient requirement. Application of previously decided rates in such scenarios could turn out to be lower or higher than the requirement. This is usually manifested as increase or decrease in nutrient use efficiencies (NUE), where decreased NUE suggests that the applied nutrient was less utilized for yield formation and may have been lost from the soil system. An unusually high NUE may mean that the crop may have experienced nutrient stress. Chlorophyll meters, leaf color charts (LCC), and GreenSeeker optical sensors are some of the promising tools developed in recent years that can help in corrective in-season N management. These tools have been extensively used by researchers to increase nitrogen use efficiency of crops (Ladha et al. 2005). Recently, Pasuquin et al. (2012) compared fixed rate of N application with standard splits and LCC-based N application and showed improved yield and nitrogen use efficiency in maize (Pasuquin et al. 2012) in Southeast Asia (Table 14.8). Research on the use of the optical sensor technology in South Asia has been carried out to evaluate its potential with the crops grown and management conditions used. The GreenSeeker sensor-based technology provides for a saving in N application of 10–20 % in comparison to blanket state recommendations, while maintaining crop yields (see http://nue.okstate.edu/GreenSeeker/India.htm and Bijay-Singh et al. 2011). Both higher N use efficiency and higher wheat grain protein were measured when the GreenSeeker was used to make N decisions. Similarly for rice, less N was used while yields were either maintained or increased. Both of these reports concluded that the optical sensor had potential to improve N use efficiency and profits for farmers through either increased productivity or profitability.

Table 14.8 Effect of N application time on yield and agronomic efficiency of irrigated maize

	Maize grain yield (Mg ha^{-1}) and agronomic efficiency (kg kg^{-1})			
	Maros (Indonesia)			O Mon (Vietnam)
Treatment	2008	2009	2008	2009
2-split fixed rate	11.2 (58.7)	10.6 (46.8)	5.4 (30.1)	6.6 (36.9)
3-split fixed rate	11.4 (62.8)	10.5 (45.8)	5.6 (31.4)	6.7 (37.6)
3-split LCC1	12.3 (64.8)	11.1 (47.0)	6.0 (30.3)	7.0 (34.7)
3-split LCC2	12.6 (65.7)	12.1 (46.4)	6.1 (30.4)	7.3 (32.4)
Mean of fixed rate	11.3 (60.7)	10.6 (46.3)	5.5 (30.7)	6.6 (37.3)
Mean of LCC	12.4 (65.4)	11.6 (46.7)	6.1 (30.4)	7.1 (33.5)
SE	1.17 (10.6)	0.93 (6.3)	0.55 (5.86)	0.36 (3.1)
Comparison of fixed rate with LCC	** (ns)	*** (ns)	** (ns)	*** (***)

*=$P < 0.05$, **=$P < 0.01$, ***=$P < 0.001$

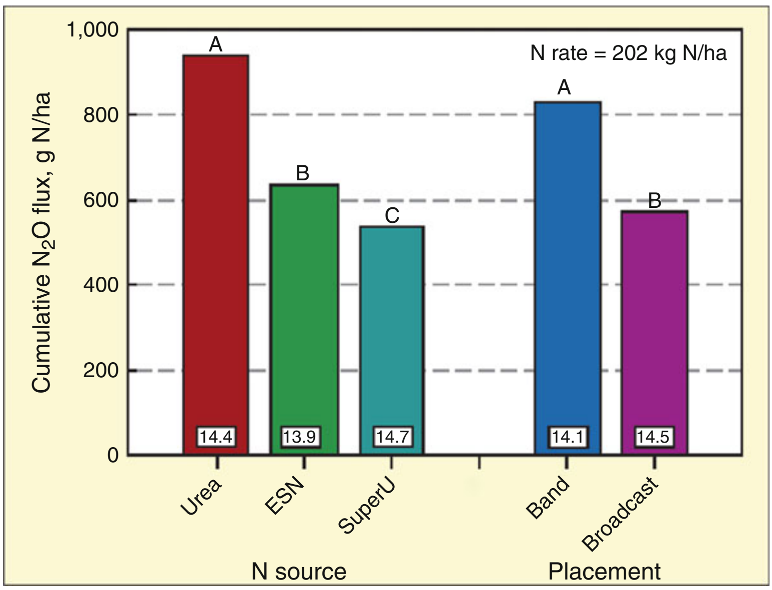

Fig. 14.4 Nitrogen source and placement effects on soil nitrous oxide (N_2O) emissions when averaged over strip-till and no-till systems (3 site years). Average grain yields (t/ha) are shown in a *white box* within each bar

14.9.4 Right Method and Nutrient Mining

Right place of fertilizer application suggests placing nutrients strategically in the soil so that a plant has access to them. Proper placement of fertilizer allows a plant to develop properly and realize its potential yield, given the environmental conditions in which it grows. Right place is, in practice, continually evolving. Plant genetics, placement technologies, tillage practices, plant spacing, crop rotation or intercropping, weather variability, and a host of other factors can all affect which placement strategy is appropriate (Majumdar et al. 2014b). In the case of phosphorus, surface applications are more prone to soluble P losses than incorporated or injected treatments (Bundy et al. 2001). Phosphorus is generally recommended for band placement in soils with high P-fixing capacity to reduce the contact with soil particles. Ladha et al. (2005) suggested that the common practice of surface broadcasting N fertilizers could entail large N losses, particularly through ammonia volatilization from the system and reduce NUE. In contrast, deep placement of urea or urea supergranules (USG) has been proven to improve NUE. Humphreys et al. (1992) noted that recovery efficiency of nitrogen was 37 % for broadcasting, 46 % for banding, and 49 % for deep point placement of USG in direct-seeded rice in Australia. In another study, Halvorson and Del-Grosso (2012) surface banded and broadcasted three N sources, urea, SuperU, and ESN, in maize to evaluate the effects of N placement on N_2O emissions under irrigated maize production. Band-applied N had a higher (45 %) N_2O emission than broadcast N averaged over 3 site years (Fig. 14.4).

14.10 Conclusion

Nutrient mining in soils have the potential to create food security challenges in South Asia. The increasing multi-nutrient deficiencies in soils across the region provide strong evidence of nutrient mining. Crop removal is the largest contributor to nutrient mining. However, there are several other avenues, such as leaching, erosion, and volatilization, through which native nutrients can be lost from soils. The loss of soil organic carbon due to high temperature and continuous tillage also makes plant nutrients vulnerable to loss in the region. Replenishing soils through adequate nutrient application based on the 4R Nutrient Stewardship approach, and rigorously factoring in nutrient offtake from the agricultural fields, is necessary to maintain soil fertility levels in intensive production systems. This will require overhauling existing nutrient management strategies prevalent in the region from a perception-based approach to a more science-based approach.

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