Interactions of Nitrogen with Other Nutrients and Water: Effect on Crop Yield and Quality, Nutrient Use Efficiency, Carbon Sequestration, and Environmental Pollution

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I. INTRODUCTION

Among the 17 essential plant nutrients, nitrogen (N) plays the most important role in augmenting agricultural production, potential environmental risks, and impacting human and animal health. Nitrogen, which is required in the greatest quantity of all mineral nutrients absorbed by plant roots, is an essential component of protein. While the beneficial effects of fertilizer N application on crop production are well documented, concern on the long-term role of fertilizer N in maintaining soil productivity, crop quality (including elemental composition and balance, protein, oil, fatty acids), and environmental safety is being expressed more frequently in recent years.

The long-term strategy of N use in agriculture likely will involve increased reliance on fertilizer N, biological N fixation (BNF) by leguminous crops, and wastes (including farm, urban, and industrial wastes) and their efficient management. Recovery of applied N by crops in field experiments has been found commonly ranging from 25 to 34% for rice (*Oryza sativa* L.) and 40 to 60% for other crops, with the global average value of about 50% (Mosier, 2002). Unutilized N may remain in the soil in various forms and/or get lost through several processes, including NH_3 volatilization, denitrification, and nitrate leaching, which have been discussed in detail in several reviews (Aulakh *et al.*, 1992; Carpenter *et al.*, 1998; Goulding, 2004; Guillard *et al.*, 1995; Malhi *et al.*, 1991, 2002a; Singh *et al.*, 1995; Zhang *et al.*, 1995). For enhancing applied nitrogen use efficiency by crops (NUE), several management techniques have been developed for different soils, crops, seasons, and regions. Examples of these include (a) integrated and judicious use of chemical fertilizers and organic manures, (b) synchronizing N supply with crop need by split applications during crop growth, (c) reducing loss of applied N with nest or band placement or large urea granules in soil, and (d) use of slow-release fertilizers and nitrification inhibitors (Aulakh, 1994; Keeney, 1982; Malhi and Nyborg, 1985, 1988; Nyborg and Malhi, 1992).

The amounts of different nutrients absorbed by a crop from soil may vary 10,000-fold, from 200 kg of N ha^{-1} to less than 20 g of Mo ha^{-1}, and yet rarely do these nutrients work in isolation. As agriculture becomes more intensive, the extent and severity of nutrient deficiencies and the practical significance of nutrient interactions increase. Interactions among nutrients occur when the supply of one nutrient affects the absorption, distribution, or function of another nutrient (Robson and Pitman, 1983). In crop production, nutrient interactions assume added significance by affecting crop productivity and returns from investments made by farmers in fertilizers. Interaction between two or more nutrients can be positive (synergistic), negative (antagonistic), or even absent (reflected as additive effect). When the effect of one factor (e.g., nutrient) is influenced by the effect of another factor, the two factors are said to interact. When the crop yield reaches an early plateau, it may be due to the limiting supplies of another nutrient illustrating the operation of Liebig's "law of the minimum" (Cooke and Gething, 1978). When that nutrient is supplied, yield will continue to increase until another factor becomes limiting. When solar radiation, temperature, and soil water availability are nonlimiting, plant nutrient requirements will be higher; for which Wallace (1990) proposed the "law of the maximum" in contrast to the "law of minimum." The law of maximum states that when the need is fully satisfied for every factor involved in the process, the rate of the process can be at its maximum potential, which is greater than the sum of its parts because of a sequentially additive interaction (Wallace, 1990). Production of field crops has already entered into the stage of multiple nutrient deficiencies management. For instance, in south Asia, a farmer in the rice–wheat belt needs to manage four to six nutrients to safeguard and sustain an annual harvest of 10 tons grain ha^{-1}, whereas a tea planter in India targeting for a yield of over 4.5 tons tea ha^{-1} must worry about seven to eight nutrients. Thus, when the combined effect of two factors is more than their additive effects, the interaction is positive. When their combined effect is less than their additive effects, the interaction is negative. Therefore, just because factor A + factor B plot produces a higher yield than either A-treated or B-treated plot does not mean that there is a positive $A \times B$ interaction. A brief review on the interaction effects of N with P, K, S, and Cu has been given previously (Aulakh and Malhi, 2004).

As N function in plant growth and nutrition is closely connected to C, the C/N ratio controls N availability and potentially affects interactions through the processes of organic residue decomposition and soil organic matter (SOM) formation in soil, biomass production (photosynthesis minus respiration) in plant, and energy flow in and through all levels of the ecosystem (Wilkinson *et al.*, 2000). An understanding of the nature of different interactions, factors affecting them, and the ways and means of managing these for useful purposes is vital for developing, advocating, and practicing a balanced and efficient crop nutrient management strategy. Identification and exploitation of positive interactions hold the key for increasing returns in terms of crop yield, produce quality, and nutrient use efficiency from applied N.

Knowledge of the negative interactions is equally valuable because the test of "precision crop nutrition" lies in the ability to minimize the losses from antagonistic effects. Nutrient interactions have a role to play in determining the course and outcome of two major issues of interest in fertilizer management, namely balanced fertilizer input and efficient fertilizer use.

This article reviews and analyzes the available information to (a) examine the impact of interactions of applied N with other nutrients, nutrient cycles, and water on NUE, (b) consider the influence of NUE on the utilization of other nutrients and water, and on C sequestration and storage in soil, (c) compute relative consumption of major fertilizer nutrients (N, P, and K) for assessing their over, under, or balanced use in different regions, and (d) pinpoint the gaps in knowledge for future research needs to optimize the use of N and other nutrients for sustainable crop production and reducing environmental risks. The fertilizer use efficiency indicators considered in this chapter are (i) agronomic efficiency calculated as production of grain over control per unit of applied fertilizer nutrient (Novoa and Loomis, 1981), (ii) improvement in nutrient uptake as measured by apparent recovery efficiency, namely uptake of fertilizer nutrient by plant over control per unit of applied fertilizer nutrient (Dilz, 1988), and (iii) improvement in crop quality parameters such as protein, oil, and fatty acid content. Similarly, water use efficiency (WUE) computed as (i) crop yield m^{-2} field area m^{-1} water used and (ii) crop yield m^{-2} field area m^{-1} water transpiration or evapotranspiration is considered here. As the impacts can be on a local, regional, or global scale, examples have been cited for different levels. Emphasis is placed on the cereal crops that occupy more than 50% of the harvested area of crop land and contribute more than 75% to annual world food production, but other field crops, such as oilseeds and pulses, vegetables, horticultural crops, and perennials are also discussed. Keeping the practical utility of research in view, a preference has been accorded to results obtained from field experiments over greenhouse and pot culture studies.

II. NITROGEN × PHOSPHORUS INTERACTION

The majority of soils around the globe are deficient in available N and are either low or medium in available P. These two nutrients account for a major share of the current annual fertilizer consumption (IFA, 2003). The N × P interaction can, therefore, be termed the single most important nutrient interaction of practical significance. This interaction is often synergistic, occasionally additive, and, in rare cases, may be antagonistic. The synergistic interactions between N and P help explain the effect, when applied as a banding beneath seed, on root growth and proliferation.

A. Cereals and Millets

It has frequently been shown that in a highly P-deficient soil, application of N alone has little impact on crop yields but N + P application can dramatically increase the response to applied fertilizer (Table I). The contribution of a synergistic interaction between N and P in cereals can be 13 to 89% of the yield response to N + P and 14 to 96% of NUE, depending on the yield potentials, level of soil fertility, and nutrient application rates. If a soil is more deficient in P than N, then application of N alone could cause a severe reduction in grain yield, as was observed by Sinha *et al.* (1973) in wheat (*Triticum aestivum* L.). Since application of P alone raised wheat grain yield by 682 kg ha^{-1}, the interaction impact was 79% on grain yield (Table I). Several studies show that crop yield and nutrient recovery are higher in N + P-treated plots than with N or P alone. For example, the composite response based on a large number of on-farm fertilizer trials in India showed

Table I
Influence of N × P Interaction on Nitrogen Use Efficiency (NUE) in Different Field Crops

	NUE (kg grain kg^{-1} N)[a]		Interaction impact (%)		
Crop	With only N	With N + P	Grain yield[b]	NUE[c]	Reference
Wheat	20.3 (120)[d]	25.9	26	28	Dwivedi *et al.* (2003)
	0 (120)	11.0	79	11 times	Sinha *et al.* (1973)
Rice	22.4 (120)	25.5	13	14	Dwivedi *et al.* (2003)
Corn	8.8 (120)	11.5	27	96	Singh (1991)
	32.4 (75)	40.0	89	23	Satyanaryana *et al.* (1978a)
Sunflower	8.7 (60)	13.8	46	59	Aulakh and Pasricha (1996)
Field peas	10.3 (40)	15.0	30	46	Pasricha *et al.* (1987)
Cauliflower	66.7[e] (120)	102[e]	23	355	Balyan and Dhankar (1978)
Bromegrass	23.6 (50)	30.8	−5.4	30.5	Loeppky *et al.* (1999)
IWG[f]	17.4 (50)	24.2	34.4	39.1	Loeppky *et al.* (1999)
Timothy	21.8 (50)	30.0	2.7	37.6	Loeppky *et al.* (1999)

[a][(Yield with applied fertilizer N, kg grain ha^{-1}) – (yield in control without N and P, kg grain ha^{-1})]/[amount of applied fertilizer N, kg N ha^{-1}].
[b]Interaction impact on grain yield (%) = 100 [(yield response to N + P, kg grain ha^{-1}) – (sum of yield response to N and P individually, kg grain ha^{-1})]/[sum of yield response to N and P individually, kg grain ha^{-1}].
[c]Interaction impact on NUE (%) = 100 [(NUE with N + P, kg grain kg^{-1}) – (NUE with N only, kg grain kg^{-1} N)]/[NUE with N only, kg grain kg^{-1} N].
[d]Value in parentheses indicates rate of applied fertilizer N (kg N ha^{-1}).
[e]Fresh heads.
[f]Intermediate wheat grass.

that at an application rate of 120 kg nutrients ha^{-1}, the response rates and thus fertilizer use efficiency were higher with 90 kg N + 30 kg P_2O_5 ha^{-1} than with 120 kg N ha^{-1} (Sharma and Tandon, 1992). Grain response per kilogram nutrient was higher by 11% when 120 kg nutrients ha^{-1} were distributed as 90 kg N + 30 kg P_2O_5 as compared to only 120 kg N ha^{-1}. In Vietnam, application of P reduced lodging and percentage of unfilled rice (*Oryza sativa* L.) grains caused by the use of N alone, remarkably improving yield response as well as NUE (Vo *et al.*, 1995). Also, P has been found to be a key factor for preventing the decline in rice yield and NUE during a wet season of Vietnam (Tan *et al.*, 1995). This 8-year study of Tan *et al.* (1995) further showed an increase of PUE from 100 kg grain kg^{-1} P in the absence of fertilizer N to 160 kg grain kg^{-1} P with the addition of N.

Data on N × P interactions in sorghum [*Sorghum bicolor* (L.) Moench] at four locations in India having different soils are shown in Fig. 1. In all four

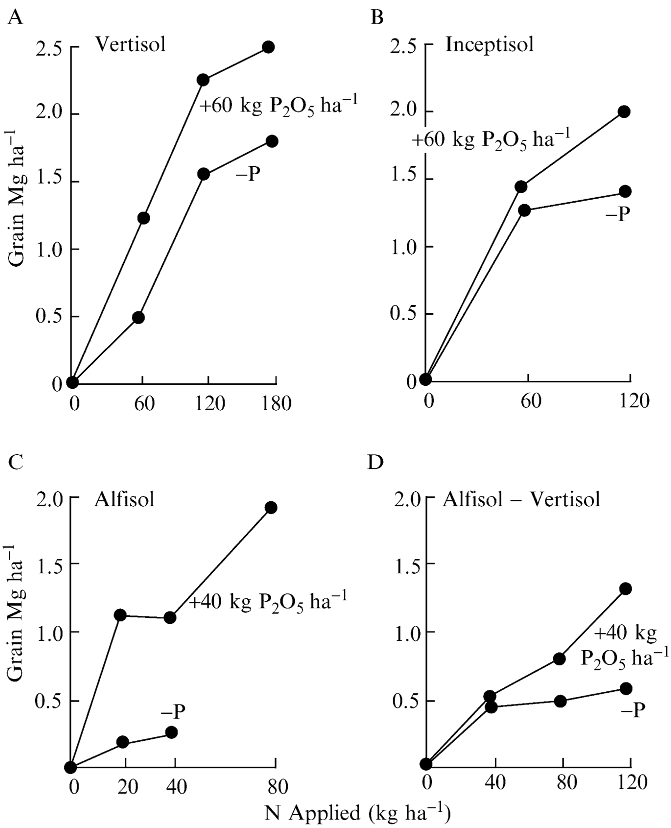

Figure 1 N × P interaction in sorghum at four locations in India. (A) Mishra and Singh (1978); (B) Roy and Wright (1973); (C) Venkateswarlu and Rao (1978); (D) Nagre and Bathkal (1979). Adapted from Sharma and Tandon (1992).

soils, the yield response to N increased when P was applied. Steeper slopes of the N + P curves as compared to N only also indicated higher fertilizer use efficiency. Graphs A and B represent sites that are moderately well supplied with available P, whereas soils of C and D are deficient in available P and show that the differences between N and N + P treatments are bigger than in A and B. Thus, in soils that are severely deficient in P, application of N alone will produce only a small increase in yield, much below the potential. In certain situations even the contribution of the N × P interaction can be large enough to overshadow the effects of N or P alone. When N is provided as an ammonium or ammonium-producing fertilizer, the acidifying effect could enhance N concentrations in plants (Malhi *et al.*, 1988) and P solubility in soil (Prasad and Power, 1997), thus providing a positive interaction. However, in those few soils that test high in available N and P, the addition of single or both element fertilizers may not provide a grain yield advantage, regardless of the type of crop, fertilizer, or its placement method (Buah *et al.*, 2000).

For nonirrigated crops, better root growth as a result of adequate P supply could enable the plants to absorb water from deeper soil layers during droughty spells, thereby increasing NUE as well. Results with rainfed sorghum in red soils show that the value of interaction effect was 10% of the total response at application rates of 20 kg N +, 20 kg P_2O_5 ha^{-1}, 20% at a dose of 40 kg N +, 20 kg P_2O_5 ha^{-1}, and 36% when each N and P were added at 40 kg ha^{-1} (Venkateswarlu and Rao, 1978). Payne *et al.* (1995) reported alleviation of water stress with P fertilization resulting in improved NUE. In early season corn (*Zea mays* L.) under dryland conditions of Bhagalpur, India, the N × P interaction was synergistic at all levels of N and P applied, but a maximum interaction advantage was derived at 120 kg N + 60 kg P_2O_5 ha^{-1} (Table I). At this level, the interaction effect contributed 27% of the total yield response to N and P and 96% to the improvement in NUE. Thus, the greater the investment in nutrients, the more the need for balance.

The N × P interaction may show different effects on the partitioning of grain and stover of various crops. For instance, the N × P interaction had a greater effect on grain than on the stover yield of sorghum (Roy and Wright, 1973) and corn (Tripathi, 1978), but the trend was opposite in millet (Maliwal *et al.*, 1989). Also, a much more pronounced interaction effect has been reported for P uptake than for N uptake by crops (Table II). The possible reason why application of N alone resulted in a large increase in P uptake was the mining of soil P. As a result of this mutual benefit, improvements in efficiency and recovery of both N and P by crops could be considerable (Table III).

Interyear variation may also be observed in the interaction pattern; the N × P effects were additive in year 1 and highly synergistic in year 2 (Satyanarayana *et al.*, 1978b). Where a farmer cannot afford to apply both N and P in optimum amounts, it is better to apply smaller or suboptimal amounts of both N and P instead of a large amount of N alone. For instance, corn grown in red soils produced 370 kg more grain with the

Table II
The N × P Interaction Effect on N and P Uptake by Sorghum Over Control Without N and P[a]

Treatment	N uptake over control	P uptake over control
Effect of N alone	58.5 kg N ha^{-1}	6.9 kg P ha^{-1}
Effect of P alone	29.2 kg N ha^{-1}	4.8 kg P ha^{-1}
Effect of N + P	95.3 kg N ha^{-1}	6.8 kg P ha^{-1}
Interaction effect	7.6 kg N ha^{-1}	5.1 kg P ha^{-1}
Interaction contribution	8%	30%

[a]Adapted from Roy and Wright (1973).

Table III
Three-Year Averaged N and P Use Efficiency and Recovery in Rice and Wheat in Rice–Wheat Cropping System[a]

Treatment	NUE[b] (kg grain kg^{-1} N)	ANR[c] (%)	PUE[d] (kg grain kg^{-1} P)	APR[d] (%)
Rice				
120 kg N ha^{-1}	22.4	39.5	—	—
26 kg P ha^{-1}	—	—	6.1	9.0
120 kg N + 26 kg P ha^{-1}	25.5	41.8	20.5	22.4
Wheat				
120 kg N ha^{-1}	20.3	45.5	—	—
26 kg P ha^{-1}	—	—	7.6	10.0
120 kg N + 26 kg P ha^{-1}	25.9	55.3	34.5	27.0

[a]Modified from Dwivedi *et al.* (2003).
[b]NUE, as explained in footnote to Table I.
[c]ANR (% recovery of applied fertilizer N) = 100 [(uptake of N with applied fertilizer N, kg N ha^{-1}) – (uptake of N without applied fertilizer N, kg N ha^{-1})]/[amount of applied fertilizer N, kg N ha^{-1}].
[d]PUE and APR, as described for NUE and ANR using P instead of N.

application of 75 kg N + 30 kg P_2O_5 ha^{-1} as compared to 100 kg N ha^{-1} without P (Satyanarayana *et al.*, 1978a).

B. Legumes

The interaction of N × P in legumes, including grain legumes such as pulses and oilseed legumes such as peanut (*Arachis hypogae* L.) and soybean [*Glycine max* (L.) Merrill], is more complex than in the case of nonlegumes. Its potential value declines once the biological N-fixing system has become functional 3–4 weeks after seeding and thus only a small starter dose of N is often sufficient. However, the interaction can also be modified by the amount of N fixed, which in turn will depend on the population and efficiency of native *Rhizobium* and whether inoculation was carried out. A weak or a negative N × P interaction probably reflects satisfactory biological N fixation (BNF) activity. This, in no way, would contradict the need for starter N along with P for legumes because grain yield increases per kilogram of applied N (20–40 kg N ha^{-1}) are substantial and very attractive in view of the high market value of pulses. For example, a 5-year field experiment revealed that fieldpea (*Pisum sativum* L.) grown without fertilizer N produced a grain yield of about 2100 kg $ha^{-1,}$ whereas the application of 20, 40, and 60 kg N ha^{-1} increased its yield to 2440, 2590, and 2710 kg ha^{-1} (Bahl *et al*., 1995).

In case the level of BNF is low, legumes may exhibit a large response to fertilizer N, as revealed by a study of Saimbhi and Grewal (1986); the yield of peas (*P. sativum* L.) increased by 2300 kg ha^{-1} or 70% with applied N, and the N × P interaction was synergistic accounting for 14% of the N + P response. In comparison, the interaction effect was less pronounced (9%) for pods $plant^{-1}$ and absent for plant height. A positive N × P interaction may indicate poor BNF and greater dependence on fertilizer N. In a field study conducted for 5 years in a loamy sand soil in the Punjab state of India, the interaction effect of N and P on yield and protein content of field peas was significant (Pasricha *et al*., 1987). For harnessing the optimum yield potential of field peas, the most effective combination was 40 kg N + 30 kg P_2O_5 ha^{-1}, where the interaction impact was 23%. In French beans (*Phasealus vulgaris* L.), while N alone was beneficial only up to 30 kg N ha^{-1}, the crop made effective use of 60 kg N ha^{-1} when this was combined with 100 kg P_2O_5 ha^{-1} (Srinivas and Rao, 1984). Compared to the control plots, French bean yields could be increased more than five times by a judicious N + P combination, of which 59% was due to the interaction effect.

Phosphate application can create more favorable conditions for BNF. While application of N alone, particularly beyond 20 kg N ha^{-1}, reduced nitrogenase activity, a balance between N and P application maintained nitrogenase activity at a high level in field peas (Fig. 2). Thus, the

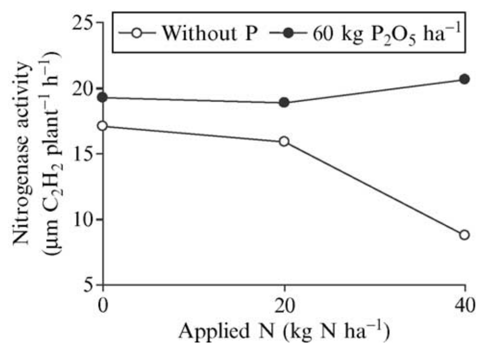

Figure 2 Effect of fertilizer N × P interaction on the nitrogenase activity of root nodules of field peas at flowering stage. Drawn with data from Pasricha *et al*. (1987).

N × P interaction is favorable for BNF in legumes enhancing N fixation, as was also observed by Muller *et al*. (1993) and Amanuel *et al*. (2000) in faba beans (*Vicia faba*). Nodulation at the late flowering stage and consequent total N yield of faba beans were significantly improved by applied P in all the three sites studied in Ethiopia (Amanuel *et al*., 2000).

C. Nonlegume Oilseeds and Other Crops

Sunflower (*Helianthus annus* L.) yield was increased by both N and P, but the interaction between the two was not synergistic (Fig. 3). However, as discussed earlier, instead of adding only N, application of both N and P at lower rates gave better returns and use efficiency. At 40 kg nutrients ha^{-1}, the combination of 10 kg N + 30 kg P_2O_5 gave 14% more yield than the application of 40 kg N ha^{-1}. In a field study in Argentina, Zubillaga *et al.* (2002) estimated that the maximum yield of sunflower can be increased by 20% with application of N and P together as compared to N alone. They suggested that P fertilization provided a more efficient use of fertilizer N by producing greater and consistent effects on crop performance most likely due to early root development. Available data on other oilseeds revealed that the interaction was positive in sesame (*Sesamum indicum* L.) (Daulay and Singh, 1982), absent in linseed/flax (*Linum usitatissimum* L.) (Thosar, 1986), and negative in castor (Venkateswarlu and Rao, 1978). Application of P to rapeseed (*Brassica napus* L.) and mustard (*Brassica juncea* L.) was more effective when combined with N, and as a general guideline, N and P_2O_5 are

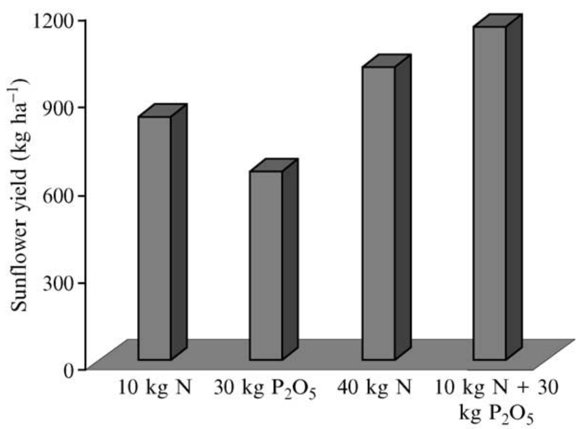

Figure 3 Influence of N × P interaction on sunflower yield. Drawn with data from Yadav *et al*. (1974).

recommended in a 2:1 ratio (Bhan, 1981; Pasricha *et al*., 1991). Application of excessive N could increase aphid infestation in rapeseed, whereas a combined application of N + P suppresses its attack and increases the yield up to 300% (Khattak *et al*., 1996).

In the case of cotton (*Gossypium hirsutum* L.), the interaction between N and P was synergistic and accounted for 15% of the response to N + P in year 1 and 29% in year 2 (Raghuvanshi *et al*., 1989). The yield of cotton seed was increased by 132% with N, by 69% with P, and by 282% with N + P.

In experiments with cauliflower, marketable yield increased from 11 tons ha^{-1} without fertilizer to 23 tons ha^{-1} with N + P (Balyan and Dhankar, 1978). No amount of N could increase the yield beyond 19 tons ha^{-1}, and the performance of 80 kg N + 50 kg P_2O_5 was superior to 120 kg N ha^{-1}. Out of the total yield response to 120 kg N + 50 kg P_2O_5, 70% could be credited to N, 7% to P, and 23% to their positive interaction.

In field experiments on the forage seed response to N and P fertilization in northeastern Saskatchewan, Canada, Loeppky *et al*. (1999) reported substantial increases in NUE of perennial grasses with combined application of N and P as compared to N alone. For example, the NUE (kg seed kg^{-1} N) values for N alone and N + P together, respectively, were 23.6 and 30.8 for bromegrass, 17.4 and 24.2 for intermediate wheatgrass, and 21.8 and 30.0 for timothy (Table I). In this study, the relative increases in grass seed yield from applied N and P were related to available N and P in soil.

Seasonal variations have also been observed in the impact of N $\times$ P interaction within the same crop species. For example, a direct response of pumpkin (*Cucurbita pepo* L.) to N and P was quite similar both in the summer and in the rainy season, but the N $\times$ P interaction was highly synergistic in summer season and absent or slightly negative in the rainy season (Sharma and Shukla, 1979). One possible reason for this differential response could be the fact that the highest yield was about 34 tons ha^{-1} in the summer season and only 14 tons ha^{-1} in the rainy season. This illustrates that nutrient interactions assume added practical importance at high-yield potentials and not at low levels of productivity. Interyear variations in N $\times$ P interaction effects were also observed in canola (*Brassica napus* L.) under western Canadian conditions, which were attributed to temperature and precipitation effects (Nuttall *et al*., 1992). Temperature increased the N and P concentration in plants primarily by enhancing their uptake rate per unit of root rather than increasing the rate of root growth (Ercoli *et al*., 1996). In the subtropics, a high temperature (26–45 °C) coupled with a high moisture status in the rainy season compared to 3–20 °C in winter enhances the solubility of native soil P and residual fertilizer P, leading to differential crop responses and fertilizer use efficiency in summer and winter seasons (Aulakh *et al*., 2003). Cultivars of the same crop species may also exhibit potentially useful specificities for fertilizer N-form preference (NO_3^- or

NH_4^+) and tolerance of NH_4^+ toxicity (Zornoza and Gonzalez, 1998), resistance to diseases (Slater *et al.*, 1991), and root morphological plasticity/capability to alter the root:shoot ratio (Johnson and Biondini, 2001) that modify nutrient interactions.

In summary, the positive N × P interaction is responsible for a sizable yield gain due to N + P application and can account for a substantial share of yield response to N + P application, leading to improvements in both NUE and PUE. The magnitude of this interaction is modified by soil type, level of available soil P, applied N and P rates, crop type, and climatic conditions. The overall trend of N × P interaction studies brings out the point that crop responses to N level off earlier, whereas those to N + P enable the crop to produce higher yields. The P-deficient crop not only produces lower yield, its stand is often nonuniform and maturity is delayed. Thus, in situations where a farmer cannot afford to apply both N and P in optimum amounts, it is better to apply lower amounts of both N and P instead of a large amount of N alone.

III. NITROGEN × POTASSIUM INTERACTION

A. CEREALS

In addition to N, potassium (K) is the major plant nutrient absorbed and removed by crops in the largest amounts among all essential nutrients. Rice, for example, a heavy remover of K from the soil, could absorb up to 30 kg K_2O t^{-1} grain produced, which is about 50% higher than N uptake; rice–wheat and rice–rice cropping systems could remove 236 and 211 kg K_2O as compared to 235 and 139 kg N ha^{-1}, respectively (Singh, 1992). After N × P interactions, N × K interactions are the second most important interaction in crop production. The significance of N × K interaction and its optimum management is increasing due to increasing cropping intensity, higher crop yield, and greater depletion of soil K. Crops with a high requirement of K such as corn and rice often show strong N × K interactions (Loue, 1978; Singh, 1992).

Plants can absorb N either in cationic (NH_4^+) or in anionic (NO_3^-) form. There is a unique possibility of anion–cation as well as cation–cation interactions with K^+. Most of the findings have illustrated that K^+ does not compete with NH_4^+ for uptake, rather it increases NH_4^+ assimilation in the plants and avoids possible NH_4^+ toxicity. Mengel *et al.* (1976) concluded that it was unlikely that K^+ competes with NH_4^+ for selective binding sites in the adsorption process. For example, when corn was grown in soil in a greenhouse at the lower rate of K application, leaf lesions occurred and the tissue yield of plants having lesions was lower with NH_4^+-N as compared to plants receiving NO_3^--N (Dibb and Welch, 1976). At the higher rate of K application, leaf lesions disappeared and the yield of NH_4^+-fed plants exceeded the yield of NO_3^--fed plants. However, there are also some reports to the contrary that NH_4^+-N reduces the K concentration in plants (Faizy, 1979).

While the response of rice to P is more or less uniformly high at all levels of applied N, the response to K increases with the amount of N + P applied (Umar *et al.*, 1986). Increasing application rates from 40 kg N + 40 kg P_2O_5 ha^{-1} to 120 kg N + 140 kg P_2O_5 ha^{-1} increased rice yield by 300 and 960 kg ha^{-1} compared with 0 and 20 kg K_2O ha^{-1}, respectively. Interestingly, application of NPK in the ratio of 120–40–0 and 40–40–20 produced similar rice yields, demonstrating higher nutrient use efficiency in the NPK treatment than with NP alone. Potassium increased rice yield by 250 kg ha^{-1} (7%) when N and P_2O_5 were applied at 40 kg ha^{-1} each, but by 910 kg ha^{-1} (24%) at 120 kg N + 40 kg P_2O_5 ha^{-1}. Increasing N and P application rates without K application is often not a sound proposition and does not increase crop yield beyond a certain level; also, higher levels of K are more effective at higher levels of N and P. Singh and Singh (1978) observed that a dose of 100 kg K_2O ha^{-1} was 2.5 times more effective in raising rice yield at 200 kg N as compared to 100 kg N ha^{-1}. Another study demonstrated that a weakly synergistic or additive N × P interaction could become highly synergistic when an adequate supply of K is ensured (Fig. 4).

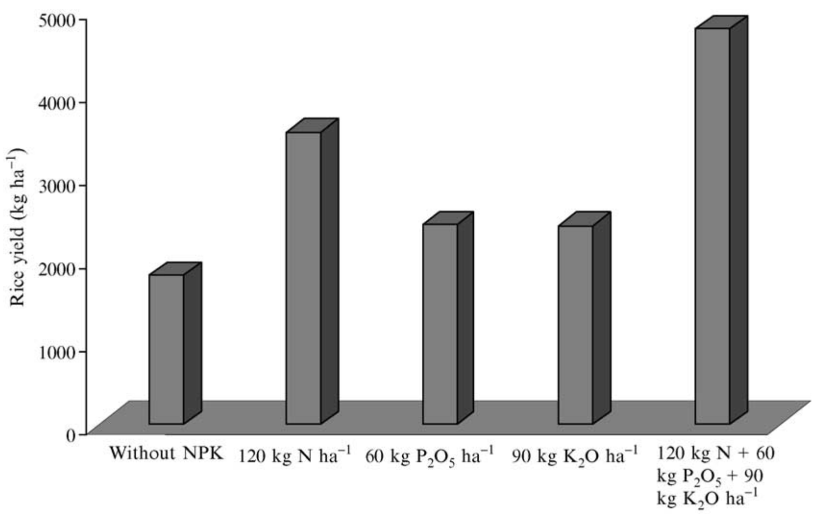

Figure 4 Influence of N × P × K interaction on rice yield. Drawn with data from Chandrakar *et al.* (1978).

Tropical soils such as Ultisols and Oxisols are poor in available P and K, and field experiments on such soils provide interesting data on N × K and N × P × K interactions. Data from Brazil show a positive N × K interaction in rice where a good response to K was obtained only when adequate N (90 kg ha^{-1}) was applied (PPI, 1988). Also, the response to N increased as the level of K was increased; the highest rice yield as well as NUE and K use efficiency (KUE) were obtained when both N and K were applied (Fig. 5). Thus, it is clear that the N × P × K interaction is helpful in increasing rice yields, provided N and P are applied at sufficient levels.

Seasonal effects on the impacts of N × K interaction are evident from rice grown during the wet and dry seasons. In a study of Mondal *et al.* (1982), the N × K interaction was more prevalent in the dry season than in the wet season, possibly because of a more favorable growing condition, higher yield, and yield potential with resultant greater nutrient demand by the crop in the dry season. In the wet season, the best rice yield was 4.3 tons ha^{-1} regardless of the level of N used, but 5.0 tons ha^{-1} rice (16% higher) could be harvested with an application of 120 N + 80 kg K_2O ha^{-1}. In the dry season, the highest rice yield with 40 kg K_2O ha^{-1} was 6 tons ha^{-1} but 7.4 tons ha^{-1} (23% more) rice could be harvested by the application of K with high levels of N. However, in some situations the interyear variations in N × P × K interactions may be difficult to explain. For instance, in the southern United States, a maximum corn yield was obtained when 168 kg N and 29 kg P ha^{-1} were applied in conjunction with 209 kg K ha^{-1} in year 1 but without K application in year 2 (Obreza and Rhoads, 1988).

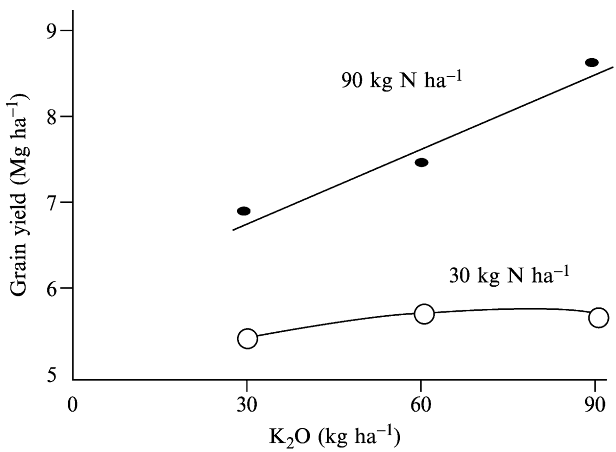

Figure 5 Effects of N and K fertilization on rice in Brazil. Adapted from PPI (1988).

Long-term experiments with the wheat crop reveal that the response of crops to K increases with time. For example, KUE in wheat was in the range of 1.7–4.2 kg grain kg^{-1} K_2O during the 1969–1971 period, which increased to 5.6–10.6 kg grain kg^{-1} K_2O during 1977–1982 (Bhargava *et al.*, 1985). When crop rotations are tested repeatedly on the same site, the situation changes; the available soil K status decreases with time due to the continuous removal by crops and changes the crop response to applied K. The response of wheat was observed only up to 30 kg K_2O ha^{-1} in a soil that tested medium in available K status (Sharma *et al.*, 1978) and up to 90 kg K_2O ha^{-1} in low K-tested soil (Azad *et al.*, 1993).

A rice–wheat double-crop system occupies 26 million ha in south and east Asia and accounts for nearly one-fourth of the region's food grain production. The alluvial soils of Indo-Gangatic plains under this rice–wheat system often show small responses to applied K, as these soils release sufficient amounts of available K from the K-rich illitic clay minerals (Aulakh and Bahl, 2001). However, in northeastern areas where high rainfall results in greater leaching losses of K, the supply of K from the soil minerals is low, the K content of groundwater is low, and significant responses of rice–wheat system to applied K could be obtained (Table IV).

Macleod (1969) demonstrated that the optimum supply of K was important in promoting barley (*Hordeum vulgare* L.) grain and straw yield, as deficient K levels had a depressing effect, especially when N was supplied at high rates. Johnson and Reetz (1995) observed that adequate soil test K levels are critical to realize the full benefit of applied N for harnessing optimum corn yields and NUE in Ohio. Also, more of the applied N was left in the soil after harvest, resulting in lower profitability and creating a greater potential for a negative environmental impact.

Table IV
Response of Rice and Wheat (kg Grain ha^{-1}) to Applied N, P, and K in Two Northeastern Districts of Punjab, India[a]

	Gurdaspur district		Amritsar district	
Treatment	Rice	Wheat	Rice	Wheat
Control	3490	1550	3950	2010
120 kg N ha^{-1}	5120	2430	5660	3600
120 kg N + 60 kg P_2O_5 ha^{-1}	5500	3090	6280	4160
120 kg N + 60 kg P_2O_5 + 30 kg K_2O ha^{-1}	5830	3440	6500	4300
$LSD_{0.05}$	160	40	150	120
Number of experiments	97	122	89	84

[a]Modified from Singh and Bhandari (1995).

B. Vegetables, Horticultural, and Plantation Crops

Because K application is commonly practiced in several nonfood crops, the N × K and N × P × K interactions are also of equal importance in maximizing fertilizer use efficiency in vegetable, horticultural, and plantation crops. Hamilton and Bernier (1975) showed that celery, carrot, and lettuce could not do well without the balanced use of N, P, and K. Earlier reviews have shown tremendous effects of N × K interaction in vegetable crops such as potato (*Solanum tuberosum* L.) and sugarbeet (*Beta vulgaris* L.) (Loue, 1978), onion (*Allium cepa* L.), chillies (*Capsicum frutescens* L.), and tomatoes (*Lycopersicon escuulentum* Mill.) (Singh, 1992); root crops such as sweet potato, cassava, and colocasia; and fruits such as banana, guava, pineapple, apple, and several other crops (Gething, 1986; Singh, 1992). In a long-term study with cassava (*Manihot esculenta* Cranz) in North Vietnam, Nguyen *et al.* (2002) observed that use of N, P_2O_5, and K_2O in a 2:1:2 ratio is most appropriate for obtaining optimum yields and tissue nutrient concentrations.

In fact, the first report of a N × K interaction was on a sugarbeet crop at Rothamsted (Hall, 1905). The crop was grown for 3 years in succession on plots annually receiving various combinations of fertilizers. The effect of applying K in addition to P was absent without N and increased by 14% at 96 kg N ha^{-1} and 36% at 206 kg N ha^{-1}. This spectacular effect of K came about partly through improvement in the yield of roots and partly because K counteracted the tendency for the sugar content to be lowered by high rates of N application. Such a phenomenon symbolizes the yield-forming role of interdependent processes such as N-driven photosynthesis and K-driven assimilation and translocation of the photosynthates. The gradient (slope) of the response to increasing N could be the same with or without K, or application of K may raise the plateau along with a change in the gradient of a crop response to N (Cooke and Gething, 1978). A third type of N × K relationship is possible where the responses to the two nutrients may show additive effects only. Fertilization with P can help enhance the ability of plants to respond to N and K fertilization, resulting in higher yields and nutrient use efficiencies (Wilkinson *et al.*, 2000).

Application of K increases the N content in grain and total N uptake by the crops, leading to improved NUE (Sangakkara, 1995). However, P and K concentrations of plants could also increase with increasing rates of applied N (Davenport and Provost, 1994; Pare *et al.*, 1993). Kemp (1971, 1983) found that the effect of increasing N bioavailability on tissue K concentrations depends on K bioavailability in the root zone. Under conditions of high K availability, increasing the N supply increases K concentration and uptake, as K concentrations decrease at high N rates because of growth dilution or another limiting factor coming into play. The role of K nutrition is well established in providing the plant the strength for facing adverse climatic conditions such as low temperature (Carrekar *et al*., 1977) and drought (Sangakkara, 1995), regulating the activity of several enzymes (e.g., protopectinase, polygalacturonase, polygalacturonate transeliminase, pectin transeliminase, and cellulases) leading to the control of diseases such as sheath rot of rice plants (Jayasekhar and Prasad, 1986), and in building up resistance in plants toward the invading pathogens. Such functions of increasing crop resistance to diseases and pests have been reviewed extensively (Perrenound, 1977). In a 76-year experiment with sweet potato in Japan, Osaki *et al*. (1995) observed excessive accumulation of N compounds, disorder of phloem transport, and restricted P absorption under K-deficient conditions. Similarly, Bussi *et al*. (2003) observed that while high N fertilization aggravated fruit pitburn ailment in an apricot orchard, K fertilization along with N minimized pitburn incidence. Thus, increasing K levels in the fertilizer prescription, especially with N, can be utilized advantageously for protecting the crops from several health hazards and, consequently, for enhancing nutrient use efficiency.

Compared to control plots of sugarcane (*Saccharum officinarum*), application of 400 kg N ha^{-1} increased cane yield by 56.8 tons ha^{-1} (133%), application of 350 kg K_2O ha^{-1} increased it by 4.7 tons ha^{-1} (11%), but combined N + K application raised it by 70.3 tons ha^{-1} (165%) (Singh, 1992). The synergistic interaction of N + K raised cane yield by 12.4 tons ha^{-1} over 200 kg N and by 13.6 tons ha^{-1} over 400 kg N ha^{-1}, accounting for about 20% of the response. In another study involving varying levels of NPK, the yield of sugarcane improved only when increasing the application of N and P was supplemented with K application (Singh, 1992).

Genotypical differences have been observed in different crops for spatial soil K exploitation. On the same soil, where crops such as sugarbeet, which have a poor root system, show a decrease in sugar yield on N + P without K plots from the beginning, cereals such as wheat, which have a dense and deep root system, may show a response to fertilizer K after several years (Orlovius, 1995).

In summary, N $\times$ K and N $\times$ P $\times$ K interactions are essentially a factor at high levels of crop productivity; strongly positive and profitable interactions are possible in crops having a high K requirement, and a significant N $\times$ K interaction can be expected wherever higher doses of N are used to increase crop production. Its benefits are (i) a reduction in the dose of N, resulting in an economy of N to the farmers, (ii) help in enabling the plant to resist the damage from pests and diseases, (iii) a favorable influence on crop quality and biochemical constituents of the produce, and (iv) minimizing the amount of fertilizer N left in the soil after harvest and reducing the potential for a negative environmental impact. Because K performs functions in plant metabolism, promoting photosynthesis, conserving moisture, and speeding up the transport of products of metabolism between different parts of the plant, harnessing the N × K and N × P × K interactions could increase the efficiency of applied N.

IV. NITROGEN × SULFUR INTERACTION

Sulfur (S) is the fourth major fertilizer nutrient along with N, P, and K. The deficiency of S has been reported with increasing frequency in the past several years all over the world (Scherer, 2001). Among different regions, Asia represents the region with the highest S fertilizer requirement. Continuous mining of S from soils has led to widespread S deficiency and a negative soil budget. There are numerous areas of the world where soils contain insufficient amounts of plant-available S to sustain the optimum growth of crops. Deficiencies of S occur most commonly on soils having low organic matter and coarse texture and those located in humid climates. The increasing S deficiencies in soils are attributable to several factors, such as (i) adoption of high-yielding crop cultivars, which demand a high fertility level and result in greater exploitation of soil reserve nutrients and removal of much larger quantities of nutrients in the harvested crop, (ii) increased cropping intensity—intensive cultivation to grow more crops annually on the same land, (iii) a drastic decline in incidental additions of S through fertilizers, atmospheric SO_2, especially around industrial cities, pesticides, and other agrochemicals, and (iv) the increased use of high-analysis S-free fertilizers (Aulakh, 2003). In the 1950s, S-containing fertilizers were common sources of N and P, as most of N as ammonium sulfate and P as single superphosphate (SSP) were applied. The consumption of fertilizer N and P has increased tremendously since then; however, the use of N and P fertilizer compounds that contain little or no S has also increased.

Both N and S are vital constituents of plant proteins and are closely associated in their synthesis and play a key role in plant oil production. Application of N in the absence of sufficient S leads to the production of amino acids that are not incorporated into proteins, and plants synthesize the required amounts of S-containing amino acids when S is applied (Finlayson *et al.*, 1970). When soils are deficient in available S, growth of all crops is drastically reduced. While N directly affects the photosynthesis efficiency of plants, S affects the photosynthesis efficiency indirectly by improving the NUE of the plants, as was evident from the relationship between N content and photosynthetic rate in the leaves of "with S"- and "without S"-treated *Brassica* plants (Ahmad and Abdin, 2000). In "without S" plants, photosynthesis was linearly related to leaf N content only up to 1.5 g m^{-2}, whereas the relationship was linear even beyond 1.5 g m^{-2} in S-treated plants. Rapeseed plants grown on S-limiting soils suppress the development of reproductive growth and could even lead to poor seed set (Nuttall *et al*., 1987; Nyborg *et al*., 1974) or pod abortion (Fismes *et al*., 2000). Glucosinolates that are produced in *Brassica* species as a result of optimum S fertilization have been effective in inhibiting soil-borne fungal pathogens, such as "take-all infection" in wheat crop (Angus *et al*., 1994).

A. Oilseeds and Pulses

Oilseeds and legumes are more sensitive to S deficiency and more responsive to S fertilization than cereals and grasses due to their higher requirements for S. The quantity of S removed from soil for optimum crop yields is highest for oilseeds, followed by pulses and the lowest for cereals (Aulakh and Chhibba, 1992). In a 3-year field study conducted on S-deficient Gray Luvisol soils in Saskatchewan, Canada, application of N fertilizer alone reduced yield, oil content, and S uptake of canola seed (Malhi and Gill, 2002a). Compared to N alone, N + S fertilization increased yield, oil content, and S uptake of seed (Table V). On six sites, average NUE was 2.0 kg seed kg^{-1} N when N fertilizer was applied alone and it increased more than five times (10.2 kg seed kg^{-1} N) when both N and S fertilizers were applied. The decline in seed yield with only N fertilization on S-deficient soils could be considered due to excessive accumulation of toxic levels of N metabolites in the plant, and adversely affecting several plant attributes as mentioned earlier. McGrath and Zhao (1996) observed an increase of 42–267% in the seed yield of *Brassica napus* with the application of 40 kg S ha^{-1} along with 180 and 230 kg N ha^{-1}. Without S application, the seed yield declined drastically due to S deficiency when the N fertilization rate increased from 180 to 230 kg N ha^{-1}. Such severe negative impacts when N alone was applied to S-deficient soils on seed yield, oil content and production, protein content, and NUE in rapeseed and mustard crops have also been observed in several other studies from Canada (Janzen and Bettany, 1984; Nuttall *et al*., 1987), India (Abdin *et al*., 2003; Aulakh *et al*., 1980,

Table V
Effect of Fertilizer N (120 kg N^{-1}) with or without S (30 kg S ha^{-1}) Application on Seed Yield Oil Content, and S Uptake of Canola in Northeastern Saskatchewan, Canada (average of Six Site Years)[a]

Parameter	No fertilizer	N alone	N + S
Seed yield (kg ha^{-1})	406	140	1228
Oil content (%)	40.5	37.3	41.4
S uptake (kg S ha^{-1})	1.0	0.4	4.4

[a]Modified from Malhi and Gill (2002a).

1995; Tandon, 1991) and Europe (Fismes *et al*., 2000; Walker and Booth, 2003). For example, a field study conducted in India on a soil testing low in available S showed 25% of the total increase in oil yield of mustard due to N + S application and a marked increase in the recovery of N and S by the crop, resulting in higher NUE and sulfur use efficiency (SUE) (Sachdev and Deb, 1990). The astounding impact of N and S on each other's recovery by the plant is illustrated in Fig. 6. Apparent fertilizer N recovery (ANR) in mustard seed increased from 25 to 42% and was accentuated from about 65 to 80% in rapeseed (seed + straw) when N and S were applied together. The trends were similar for the apparent S recovery.

Responsiveness of rapeseed to the N × S interaction may vary with site, season, form of S, and genotypes. For instance, the high glucosinolate cultivar 'Rafal' was less responsive (59%) than the very low glucosinolate cultivar 'Tapidor' (288%), with cultivar 'Cobra' (66%) coming somewhere in

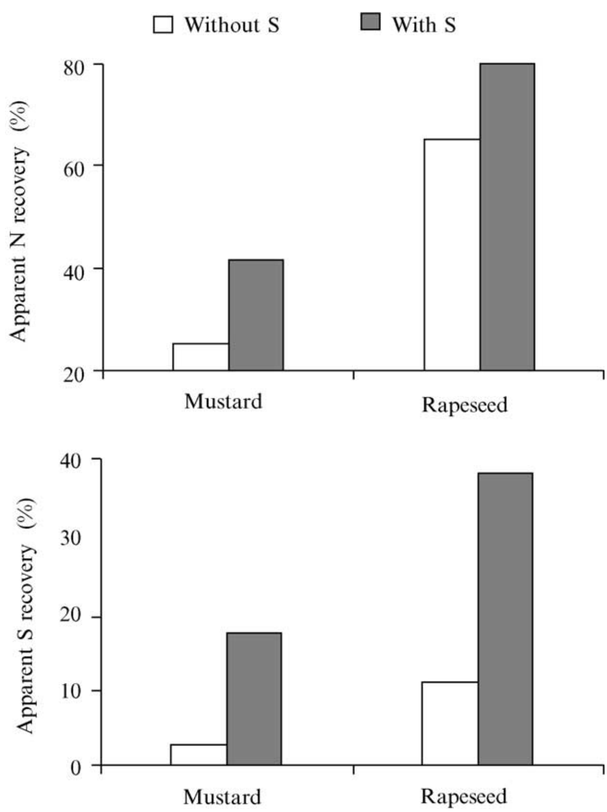

Figure 6 Influence of N × S interaction on recovery of N and S by mustard seed and rapeseed (seed + straw). Drawn with data from Aulakh *et al*. (1980, 1995).

between (Walker and Booth, 2003). The relative content of different fatty acids in some oilseeds determines its use. An adequate supply of N, P, and S accelerates the metabolic pathway of linolenic acid synthesis, as it resulted in a large decrease in the percentage of stearic, oleic, and linolenic acids with a concurrent increase in the content of linolenic acid (Fig. 7). Linseed oil, with high linolenic acid and low oleic acid, is used to manufacture paints, oilcloths, and linoleum.

Field experiments with pulses such as chickpea (*Cicer arietinum* L.), lentil (*Lens cultinaris* Medik), mungbean (*Vigna radiata*), blackgram (*Vigna mungo*), pigeonpea (*Cajanus cajan* (L.) Millsp.), and cowpea [*Vigna unguiculata* (L.) Walp] showed significant increases in grain yield due to balanced N, P, and S fertilization. For adequate rates of N + P application, the response to S varied from 3% in cowpea to as high as 20% in lentil, as was presented in earlier reviews (Aulakh, 2003; Aulakh and Chhibba, 1992; Tandon, 1991). Several studies have shown the interaction effects of S with N and K to be synergistic in influencing the yield, quality (protein and amino acid synthesis), and nutrient uptake by different pulse crops (Tandon, 1992). In the case of N × P × S interaction, a differential behavior of one nutrient in relation to the concentration or rate of application of other nutrients has been documented. For example, in a field study with soybean, adequate levels of 25 kg N, 80 kg P_2O_5, and 40 kg S ha^{-1} increased the seed and oil yield of soybean from 597 and 111 kg ha^{-1} in control to 1735 and 412 kg

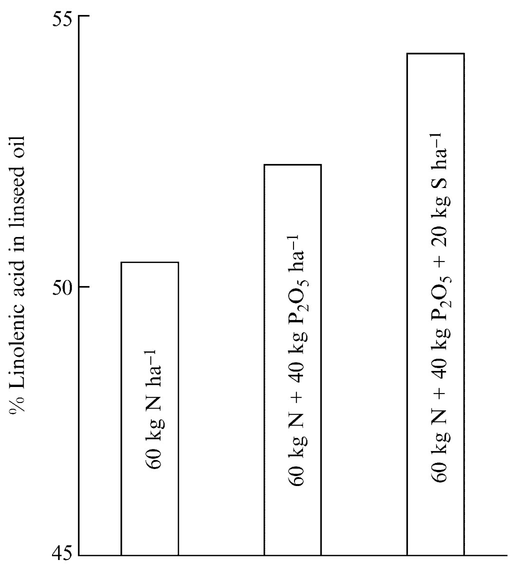

Figure 7 Influence of balanced application of fertilizer N, P, and S on the synthesis of linolenic acid in linseed oil. Drawn with data from Aulakh *et al.* (1989).

ha^{-1}, respectively (Aulakh *et al*., 1990). However, application of excessive P (120 kg P_2O_5 ha^{-1}) created an imbalance and reduced the seed and oil yields. Adsorption and desorption of anions commonly used as fertilizers such as $H_2PO_4^-$, HPO_4^{-2}, PO_4^{-3}, and SO_4^{2-} on colloidal soil surfaces occur simultaneously. Phosphate is a stronger competitor for anion adsorption sites; therefore, the large applications of P could further accentuate S deficiencies by causing concurrent desorption of SO_4^{2-}-S from soil (Pasricha and Aulakh, 1991) and its subsequent leaching with irrigation and rainwater. Such environmental problems could occur more commonly in coarse-textured soils with low organic matter, which have little SO_4^{2-} retention capacity but have high percolation rates.

B. Cereals, Millets, Vegetables, and Plantation Crops

Cereals, which have relatively low S requirement, have shown significant responses to applied S. Several studies are available revealing an average cereal grain yield response from 15 to 41% (Aulakh, 2003; Scherer, 2001; Tandon, 1991). The high proportion of significant responses is particularly noteworthy in rice and wheat.

The yield of wheat, grown in the coastal plain of Virginia, increased linearly with N + S application (Reneau *et al*., 1986). In four different field studies in India, application of S with N and P produced an additional yield of 700 to 1300 kg and 400 kg ha^{-1} of wheat and corn, respectively (Aulakh and Chhibba, 1992). In bread wheat, perhaps the most striking effect when the concentration of S in grain is decreased below a certain level is that dough properties change; the dough becomes stronger and less extensible, reducing the pop-loaf quality (Naeem and MacRitchie, 2003). The N absorbed in excess of protein synthesis requirement accumulates as nitrates, amides, and free amino acids in wheat and corn (Friedrich and Schrader, 1978; Stewart and Porter, 1969) and excessive levels of these metabolites are considered to be toxic (Steinberg *et al*., 1950).

The ^{35}S studies showed that the percentage uptake of fertilizer S in corn leaves and stems increased significantly with increasing levels of N and S due to a strong N × S interaction; conversely, application of N alone as NH_4^+ or NO_3^- resulted in a significantly higher utilization of native soil S (Dev *et al*., 1979; Jaggi *et al*., 1977). Mixing urea with elemental S in a 4:1 ratio prior to its surface application onto a calcareous soil enhanced the NUE of pearl millets from 15 to 48% while reducing the NH_3 volatilization by about 50% (Aggarwal *et al*., 1987).

In onions grown in an S-deficient soil, the highest dry matter (DM) and dry bulb yield was produced by 60 kg N + 40 kg S ha^{-1} (Sachdev *et al*., 1991). For both these parameters, the N × S interaction was synergistic and contributed

Table VI
Effect of Low and High N Rates with and without S Fertilizer Application on Fertilizer N Recovery in Onion Bulbs[a]

Treatment	Fertilizer N in bulbs
60 kg N ha^{-1} (no S)	11.8 kg ha^{-1}
60 kg N + 40 kg S ha^{-1}	18.1 kg ha^{-1} (+53%)
120 kg N ha^{-1} (no S)	17.4 kg ha^{-1}
120 kg N + 40 kg S ha^{-1}	19.7 kg ha^{-1} (+13%)

[a]Modified from Sachdev *et al.* (1991).

18–20% to the total response (Table VI). While the combined application of N and S produced the highest dry bulb yield, excessive levels of applied N produced high-moisture onions. Sulfur application markedly increased the NUE. Fertilizer N recovered in bulbs was more from 60 kg N + 40 kg S ha^{-1} than that from 120 kg N ha^{-1} without S application. Aulakh *et al.* (1977) reported a potato tuber yield of 8.4 tons ha^{-1} with the application of adequate NPK, but was increased to 12.1 tons ha^{-1} when 25 kg S ha^{-1} was also applied. A differential response among cultivars of the same crop could result in a significantly different response to S, as illustrated for four cultivars of wheat (*Triticum aestivum* L.) (Aulakh and Chhibba, 1992), coffee (*Coffea Arabica*) (Rao, 1988), and tobacco (*Nicotiana tabacum* L.) (Gopalachari, 1984).

C. Grasses, Perennials, and Other Forage Crops

In forage crops, the highest yields are generally obtained with N + S application, suggesting that the optimum ratios of N and S fertilizers must be worked out for different soils and forages. The combined application of 60 kg N + 40 kg S ha^{-1} gave a 10% extra yield increase than the sum of their individual effects in Chinese cabbage (Hazra, 1988). Although a dry forage yield of 3 tons ha^{-1} of Chinese cabbage could be obtained with an application of either 56 kg N ha^{-1} alone or 35 kg N + 40 kg S ha^{-1}, the combined use of both N and S seems to be the best choice because (i) the cost of lower rates of N + S is less than the high rate of N alone, (ii) there is a higher impact on crop quality, and (iii) there is a positive effect on long-term soil fertility for sustainable production. Aulakh *et al.* (1976) concluded that NO_3^- and other soluble N compounds accumulated in alfalfa (*Medicago sativa* L.) forage when S was not supplied in an adequate proportion to the N supply. Thus, imbalanced N:S use could lead to NO_3^- poisoning of animals that are fed on such forage. Another example of positive environmental impacts of N × S interaction was illustrated by Brown *et al.* (2000) while working with permeable grassland soil in the United Kingdom

Table VII
Two-Year Averaged N Uptake by Perennial Grass, N Denitrified and Leached, and Nitrate-N Concentrations in Leachate in a Permeable Halse Soil of the United Kingdom with Application of Low and High Rates of N with or without S (Adequate P and K Applications Were Given)[a]

	200 kg N ha^{-1}		450 kg N ha^{-1}	
Parameter	Without S	With S	Without S	With S
N uptake (kg N ha^{-1})	165	207	278	332
N denitrified (kg N ha^{-1})	18.9	9.6	18.5	12.5
N leached (kg N ha^{-1})	5.2	3.6	52.1	17.5
Peak nitrate-N concentration (mg N l^{-1})	1.8	1.3	28.4	7.9

[a]Modified from Brown *et al.* (2000).

(Table VII). Application of the optimum amount of S along with N could drastically reduce NO_3^- leaching, leading to a significant increase in herbage DM by 27% and N uptake by 26%.

In a 13-year field experiment on a Dark Gray Chenozem loam soil in Saskatchewan, average forage DMY was 1.41, 4.64, and 5.32 tons ha^{-1} $year^{-1}$ for an unfertilized control, 112 kg N + 11 kg S ha^{-1}, and 112 kg N + 11 kg S + 40 kg K ha^{-1} treatments, respectively (Nyborg *et al.*, 1999). Averaged over 13 years, NUE was 8.4 kg DM kg^{-1} N $year^{-1}$ with the application of N alone and increased more than four times to 41.4 kg DM kg^{-1} N $year^{-1}$ when S fertilizer was applied in combination with N. Application of K fertilizer in addition to N and S further increased the NUE to 47.5 kg DM kg^{-1} N $year^{-1}$. In field experiments in Arkansas, the highest N recovery by coastal bermudagrass was reported where S was applied along with N (Phillips *et al.*, 1995). Similarly, S recovery increased with increasing N rate (Phillips and Sabbe, 1994).

In a field study on N and S fertilization of pasture oats in China, Wang *et al.* (2002) suggested that application of S fertilizer is the most appropriate way to increase forage productivity, quality, and N fertilizer use efficiency, as well as meeting S requirements of grazing sheep on S-deficient soils. In this experiment, a combined application of N and S gave a much higher dry matter and protein yield, DM digestibility, and average daily weight gain of sheep compared to N or S alone (Table VIII). Sulfur utilization from soil increased from 22.2% with S alone to 32.6% with N + S and increased from S fertilizer from 20% with S alone to 28% with N + S together.

In summary, the studies clearly demonstrated that for economic and stable production, both N and S should be applied in appropriate ratios. Collectively, the results indicate that adequate N and S nutrition during plant growth is highly desirable and their application at optimum rates is required to improve the efficiency of one another not only for crop yield but also for produce quality in relation to protein, oil production, and fatty acid

Table VIII

Effect of Fertilizer N (138 kg N^{-1}) with or without S (30 kg S ha^{-1}) Application on Forage Dry Matter Yield (DMY), Protein Yield (PY), N and S Content, N:S Ratio, DM Digestibility, and Weight Gain of Sheep in a Pasture Experiment on Oats in China[a]

Fertilizer treatment	DMY (kg ha^{-1})	PY (kg ha^{-1})	N content (%)	S content (%)	N:S ratio	DM digestibility (%)	Average daily gain of sheep weight (g day^{-1})
No fertilizer	4753	606	2.04	0.14	14.40	59.5	105.2
N only	8154	1180	2.32	0.12	19.51	62.3	139.3
S only	5276	674	2.04	0.24	8.51	61.6	106.7
N + S	9104	1375	2.42	0.20	12.03	69.0	173.3

[a]Modified from Wang *et al.* (2002).

content. The N × S interaction studies indicate that maximum yield is only attained when the two nutrients are provided in a balanced way and correct diagnosis of nutrient deficiency is vital. If a S deficiency is misdiagnosed as an N deficiency and additional N is applied as a consequence, then the crop growth would be adversely affected and a greater penalty would result in terms of crop yield and quality, nutrient use efficiency, and excessive accumulation of NO_3^- and other toxic metabolites in forages, plus negative environmental effects such as leaching of NO_3^-, denitrification, and ammonia volatilization. The response of crops to N × S interaction, however, could vary according to site, season, form of S, crop, and genotype.

V. NITROGEN × CALCIUM AND NITROGEN × MAGNICIUM INTERACTIONS

Although Ca requirements for plant growth and metabolism are low, it has great significance in balancing levels of other nutrients, including N. Fertilization with NO_3^--N generally enhances the Ca and Mg concentration in plants driven by the need for a cation–anion balance. When N is supplied as NO_3^--N, electrical neutrality is maintained internally by its reduction in synthesizing organic acids by the release from roots of anions such as OH^- or HCO_3^- or by the uptake of cations (Wilkinson *et al.*, 2000). When N is supplied as NH_4^+-N, internal electrical neutrality is maintained by the release of H^+ or by uptake of anions. Application of lime and farmyard manure (FYM) significantly increased water-soluble N and fixed NH_4^+ in the acidic soils of India, leading to increased N uptake by soybean and wheat (Bishnoi *et al.*, 1984; Prasad *et al.*, 1986). In a highly acidic soil (pH 4.5), a substantially higher rice yield obtained with the combined application of lime and NPK than with NPK or lime alone indicated that soil acidity is the main constraint in the utilization of soil nutrients by the crop (Fageria and Baligar, 2001). Once acidity is corrected, the uptake of soil N, Ca, and some other nutrients increases many folds. Other associated problems, such as high concentrations of Al and Mn, reduced BNF, and decreased root growth, may lead to a decline in water and nutrient use efficiencies. In one of the experiments conducted by Malhi *et al.* (1995a) in the Prairie Provinces of Canada, the grain yield of barley was 2.1 tons ha^{-1} without lime and 3.1 tons ha^{-1} with lime at a 50 kg N ha^{-1} rate (i.e., an increase of NUE by 20 kg grain kg^{-1} of applied N) and was 2.3 tons ha^{-1} without lime and 3.5 tons ha^{-1} with lime at a 100 kg N ha^{-1} rate (i.e., an increase of NUE by 12 kg grain kg^{-1} of applied N). These findings suggest that on acid soils, crops fertilized with N would show a yield and NUE advantage from lime.

Sodic Solonetzic soils are also deficient in Ca for optimum plant growth and can be reclaimed by applying gypsum to replace Na^{+} with Ca^{2+} on the cation-exchange sites. In a Black Solonetzic soil in Alberta, Canada, an application of gypsum increased the concentration of extractable Ca and reduced the sodium adsorption ratio (Malhi *et al.*, 1992). In this experiment, a N $\times$ Ca interaction not only improved the soil chemical properties and crop yield, but also enhanced the concentration of Ca, K, and Zn in the flag leaf of barley while decreasing Na concentration.

VI. NITROGEN × MICRONUTRIENTS INTERACTIONS

Deficiencies of different micronutrients are not widespread, but whenever they occur, they can result in a serious reduction in grain yield and quality of crops and utilization efficiency of other nutrients and water. However, in certain situations, more than one micronutrient can become deficient and are needed for optimum crop production and quality. For instance, field experiments on corn in Egypt showed that sowing of corn seeds soaked in a Zn, Mn, and Fe mixture could enhance NUE, leading to a remarkable improvement in grain yield, N recovery, and saving of N fertilizer, and at the same time reduced the potential for pollution of soil and groundwater from leached nitrate-N (Teama, 2001).

A. Zinc

Enhanced crop growth due to applied N at a marginal level of Zn in soil often induces Zn deficiency, causing a decline in the crop response to N itself. Practically, a N $\times$ Zn interaction is an important factor in nutrient management for all those field crops that require moderate to high amounts of N ((Bajwa and Paul, 1978; Kene and Deshpande, 1980; Kumar *et al*., 1985; Sakal *et al*., 1988; Verma and Bhagat, 1990). For instance, as the N supply to rice increased, Zn deficiency became more acute (Singh and Singh, 1985). In another field study, application of $ZnSO_4$ increased the response of rice to urea-N by 400 to 600 kg grain ha^{-1} (Savithri and Ramanathan, 1990). Thus, N and Zn showed synergistic effects and the best yield could be obtained with the optimum combination of both. When this optimum combination of N and Zn for obtaining best yield is disturbed either by high doses of N or Zn, the yield generally decreases. In a field experiment on a sandy loam calcareous soil of Bihar, India, maximum benefits from Zn application were derived only under an optimum supply of NPK (Table IX).

Nitrogen application has been reported to influence Zn absorption by plants and vice versa. In corn, the Zn concentration in shoots was highest when both N and Zn were applied together followed by the application of Zn alone, N alone, and no-fertilizer treatment in descending order (Dev and Shukla, 1980). This shows that for maximum utilization of native soil Zn or applied Zn, the presence of adequate amount of N is essential. The differences among N sources with regard to efficiency of Zn utilization may be attributed to the effect of the accompanying anion on the mobility of Zn as well as to the reduction in soil pH, which enhances Zn availability. Application of 200 mg N kg^{-1} soil through $(NH_4)_2SO_4$ caused a decrease in soil pH from 8.4 to 7.9 three weeks after its application, leading to the increase in soil-available Zn from 0.34 to 0.49 mg kg^{-1} soil (Dev and Mann, 1972). An adequate supply of N also enhanced the translocation of Zn from roots to other parts of pearl millet plants in the presence of applied N (Kumar *et al*., 1985).

The synergistic N × Zn interaction has also been reported to increase the N concentration in different crops (Hulagur and Dangarwala, 1983; Kene

Table IX
Effect of Different Zinc Levels without and with N, P, and K Application on Grain Yield of Wheat (kg ha^{-1})[a]

Treatment			Rate of Zn (kg Zn ha^{-1})		
N (kg N ha^{-1})	P (kg P_2O_5 ha^{-1})	K (kg K_2O ha^{-1})	0	5	10
0	0	0	1450	1580	1640
50	30	25	2730	2880	3030
100	60	50	3530	3840	4040
$LSD_{0.05}$				220	

[a]Modified from Sakal *et al*. (1988).

and Deshpande, 1980; Singh and Tripathi, 1974), as Zn helps accelerate protein synthesis and the BNF efficiency of legumes. Application of 5 mg Zn kg^{-1} soil significantly increased the BNF by cowpea to 156.7 kg ha^{-1}, relative to 129 kg ha^{-1} for a no-Zn control (Yadav *et al.*, 1984). The better utilization of N due to a synergistic N × Zn interaction could also markedly increase the energy values, carbohydrates, total lipids, and lysine and histidine amino acids in addition to proteins in cereals as well as in legumes (Dwivedi and Randhawa, 1973; Kene and Deshpande, 1980).

B. Copper and Manganese

Numerous reports suggest that N × Cu interactions could be synergistic or antagonistic. Camp and Fudge (1939) were the first to report that Cu deficiency symptoms became more severe when N was applied to Cu-deficient soils. Thereafter, this was confirmed by a number of studies. Copper-deficient citrus leaves were found to contain a higher amount of N than Cu-sufficient leaves (Camp and Fudge, 1939). However, in *Brassica juncea*, an antagonistic N × Cu interaction was observed only when both were in excess supply (Antil *et al.*, 1988). At lower levels of Cu (2.5 and 5 mg Cu kg^{-1} soil), the effect of N on Cu uptake was synergistic. It has been reported that cereals having protein-rich grains are more susceptible to Cu deficiency than those poor in grain proteins (Nambiar, 1976).

Wheat grown on Cu-deficient soils is highly susceptible to the disease "stem melanosis" caused by *Pseudomonas cichorii*, which could be effectively controlled by the application of Cu (Malhi *et al.*, 1989; Piening *et al.*, 1987). In a 3-year field experiment with wheat receiving 110 kg N ha^{-1} on a Cu-deficient soil in Saskatchewan, the no-Cu control plot produced 1566, 1620, and 1262 kg grain ha^{-1} in 1999, 2000, and 2001, respectively (Malhi *et al.*, 2003b). The corresponding grain yield with a foliar application of 0.25 kg Cu ha^{-1} as Cu chelate-EDTA at the flag-leaf growth stage was 2709, 2675, and 2641 kg ha^{-1}. While the NUE with the N alone ranged from 9.3 to 12.0 kg grain kg^{-1} N, it increased to 19.6–20.1 kg grain kg^{-1} N with the N + Cu application.

The availability of Mn is controlled by the total quantity of Mn, pH, SOM, and redox potential in soils. Manganese uptake can be stimulated by either or both forms of N. The NO_3^- form may lead to a greater uptake of Mn^{2+}, whereas the NH_4^+ form may increase the bioavailability of Mn by acidification. Schomberg and Weaver (1991) showed that Mn decreased BNF in arrowleaf clover (*Trifolium* sp.) more than mineral N uptake. Consequently, the potential impact of excess soluble Mn in the root zone was partially offset by the availability of mineral N for uptake and metabolism.

C. Iron, Boron, Cobalt, and Molybdenum

The interaction of N with Fe, B, Co, and Mo is of great economic significance, especially in legumes. This is because these four micronutrients are closely associated with steps in the process of BNF.

Iron is an integral part of nitrogenase, ferrodoxin, leghaemoglobin, and cellular enzyme systems in nodules (Evans and Russel, 1971). When Fe and Zn are in short supply in soils, *Rhizobium* fails to function and fix N_2, as has been observed in French beans (Garg, 1987). An application of 5–10 mg Fe kg^{-1} soil alone or in combination with Zn developed N-fixing nodules and increased the yield of French beans, leading to a remarkable increase in NUE. Most of soil Fe is present as unavailable Fe(III), which must be reduced to the Fe^{2+} form before plants can take it. The acidic nature of some N fertilizers enhances the availability of micronutrient cations including Fe in soils. In neutral to alkaline soils with low available Fe, increased acidity with NH_4^+ may enhance the availability of Fe^{2+} by promoting the reduction of Fe(III). In a sand culture experiment, irrespective of the Fe source (Fe-citrate, Fe-EDTA, Fe-EDDHA), the iron requirement for the normal growth of rice plants receiving N in the form of nitrate or urea was about four times higher than that of plants receiving N as ammonium nitrate (Takkar *et al.*, 1989). The uptake of N by several rice cultivars grown on sandy loam soil increased at the lower dose of Fe, but was reduced at higher levels of iron (Tandon, 1982). Such behavior could be due to a reduction in yield because of excessive Fe or the ability of plants to utilize Fe efficiently at lower application rates.

Boron is important for the synthesis of glutamine, development of nodules in legumes, and pollen tube growth. Application of B increased the N concentration in chickpea (Yadav and Manchanda, 1979), lentil (Singh and Singh, 1983), and peanut (Patel and Golakia, 1986), presumably due to the favorable effect of B on nodulation as nodule counts were found to increase by 37% over no-B control (Patel and Golakia, 1986). Conversely, increasing rates of N significantly decreased the boron concentration in wheat, barley, and alfalfa at the boot stage, illustrating that N application is helpful in alleviating B toxicity in soils low in available N (Aggarwal and Yadav, 1984; Gupta, 1976; Willett *et al.*, 1985). However, optimum use of B is very much necessary as indiscriminate use of B could cause B toxicity in plants. For example, application of B beyond 3.5 mg kg^{-1} soil in sandy loam and 4.5 mg kg^{-1} soil in clay loam soil becomes toxic to chickpea (Singh *et al.*, 1976), illustrating that the safe and toxic limits differ with soil texture.

Cobalt is required by *Rhizobium* for fixation of N_2 in legumes as it plays a vital role in the formation of vitamin B_{12}, which is essential for the formation of hemoglobin. However, studies demonstrating the impacts of N $\times$ Co interaction on NUE are lacking.

Molybdenum is important for the nutrition of legumes, as it is essential for the activity of enzyme nitrogenase. Application of 2 mg Mo kg^{-1} soil significantly improved nodulation, dry weight of nodules, leaf area, shoot dry weight, N content, and yield of French beans (Acharya and Biswas, 2002). In a study with Dark Yellow Oxisol soil in Brazil, the application of 10 kg urea-N ha^{-1} at planting and 40 kg N ha^{-1} side dressed in conjunction with 20 kg Mo ha^{-1} by foliar spray resulted in the highest grain yield and consequently NUE in dry beans (Fullin *et al*., 1999). Molybdenum is also essential for NO_3^- reduction in nonlegumes, and hence NUE and crop quality. While summarizing the interactive effects of Mo with other nutrients, Gupta (1997) concluded that N applications over time might decrease Mo uptake. Part of the N × Mo interaction may arise from the opposite effects of NH_4^+ and NO_3^- forms on soil pH, which would change Mo availability.

VII. NITROGEN × WATER INTERACTION

Water and N are the most important factors controlling crop growth and grain production. Soil moisture conditions affect the availability, movement, and uptake of nutrients by crops. Ideally, for the most efficient use of soil and fertilizer N, adequate quantities of water must be available throughout the crop growth period. Among different factors that influence the NUE, water seems to be the most critical. Much of the increase in the yield and quality of field crops during the last half century has been due to improved cultural practices, including increased soil water supply, which is frequently the limiting plant growth factor even in humid tropics. Thus, it is not surprising that the provision of irrigation facilities, especially where groundwater is of good quality, has rapidly expanded crop production and enhanced crop yield.

Water is stored in the soil before it is taken up by plants via its roots and is then transported to foliage and is lost to the atmosphere through transpiration. Thus, retention and movement of water within soil, proliferation of the root biomass in the soil profile, and uptake of soil water by plants in relation to atmospheric evaporative demand determine WUE. Therefore, impacts of the N × water interaction are, to a large extent, controlled by plant roots, which help the crop maintain effective capacity for absorbing nutrients as well as water, and more so from subsoil. In addition to several other factors (discussion of which is beyond the scope of this review), the time and extent of soil wetting have profound effects on the root development of crops, which in turn determine the water extraction pattern of crops, as has been shown for the response of dryland wheat to wetting patterns varying from year to year (Singh *et al*., 1975). Gajri and Prihar (1985) revealed that the 2-year mean root mass densities of wheat in 0- to 180-cm and 30- to 180-cm soil layers were 70 and 140% higher in early postseeding irrigation than without it. Gajri *et al*. (1989) illustrated that early wetting not only increased root biomass and length, but also influenced the rate of downward root extension. Selection of crops and cropping sequences for high WUE and NUE are dictated by the availability of water. Because the water availability spectrum vis-à-vis NUE is quite different under (i) rain fed or dryland and (ii) partially or fully irrigated environments, these are hence discussed separately.

A. Dryland Environments

The amount and intensity of precipitation, melting snow, topography, infiltrability, and water retentivity of soil, and depth of root zone determine the amount of plant-available soil water. The crop yield response and recovery of applied N are influenced by the soil water status in several ways. While inadequate soil moisture results in poor crop growth, leading to a reduced uptake of nutrients and low NUE, excessively wet soil conditions cause substantial N losses by leaching and denitrification of NO_3^--N, resulting in low NUE.

In many dryland areas, the yield response of crops to fertilizer N is related to the total amount of precipitation (Campbell *et al*., 1993a; Nuttall *et al*., 1992). With an average rate of 60 kg N ha^{-1}, Nuttall *et al*. (1992) obtained a canola seed yield of 2460 kg ha^{-1} in a year with 162 mm of rainfall in the growing season, whereas seed yield was only 370 kg ha^{-1} in a year with 95 mm rainfall. In a 22-year study with bromegrass (*Bromus inermis* Lyess) in Alberta, 112 kg N ha^{-1} increased the forage yield from 4.3 to 6.6 tons ha^{-1} when precipitation in the growing season increased from 116 to 256 mm (Malhi *et al*., 2004c). In a field investigation in China, recovery of applied N increased from 6.4% in drought years to 58.6% in high or normal rainfall years (Dang and Hao, 2000).

Under rain-fed conditions, it is not only the total water that becomes available in a season, but also its time of availability during the crop growth period that affects the NUE. Sandhu *et al*. (1992) showed that the amount and distribution of rainfall during two main phases of crop development (vegetative and reproductive phases) greatly influenced the NUE of rain-fed wheat. Seasonal rainfall of less than 150 mm, received as half in the vegetative phase and the other half in the reproductive phase (1:1 distribution), was more effective than 2:1 or other patterns in increasing the wheat grain yield. However, for seasonal rainfall exceeding 150 mm, the 2:1 distribution between vegetative and reproductive phases was more effective than the 1:1 distribution. The additional rainfall of 100 mm received in the 2:1 pattern reduced the N requirement for a given yield by 30 to 49 kg N ha^{-1} compared with the same rain received in the 1:1 fashion. In studies with dryland wheat in Saskatchewan, in addition to the amount and distribution of rainfall during two main phases of crop development, the available moisture storage at seeding also affected the NUE (Read and Warder, 1974). Thus, Selles *et al.* (1992) suggested fertilizer recommendations according to different levels of available water, which soil testing labs have adopted.

Conservation of soil moisture, for example, by eliminating tillage and mulching, would thus enhance crop yields and NUE. In a field experiment on a Gray Luvisol soil of Alberta, an increase in the grain yield of barley with an application of 50 kg N ha^{-1} was 570 kg ha^{-1} under zero tillage (ZT) as compared to 410 kg ha^{-1} under conventional tillage (CT) (Izaurralde *et al.*, 1995). The significantly higher NUE of 11.4 kg grain kg^{-1} N under ZT as compared to 8.2 kg grain kg^{-1} N under CT (Izaurralde *et al.*, 1995) was most likely achieved by conserving more soil moisture under ZT (Aulakh and Rennie, 1986; Bonfil *et al.*, 1999; Malhi and O'Sullivan, 1990; Nyborg and Malhi, 1989). While working with a ZT system, Campbell *et al.* (1993b) also observed an excellent relation between dryland wheat yield and available water, fertilizer N rate, and soil nitrate-N. The conservation of moisture as determined by topography or landform within a field could influence crop yields, NUE, and WUE. For example, a concave landform, which retains more spring soil moisture than a convex position after melting of snow, provided a greater yield response of canola to fertilizer N, higher N uptake, and recovery of applied ^{15}N (Malhi *et al.*, 2004b; Pennock *et al.*, 2001).

In perennial grassland experiments in Alberta and Saskatchewan, NUE of 34–44 kg DM kg^{-1} of applied N was more than double in relatively moist areas than the 11- to 19-kg DM kg^{-1} N obtained in dry areas (Malhi, 1997; Malhi *et al.*, 1997a, 2004a). From data in ^{15}N-labeled experiments in various parts of the world, several researchers (Malhi, 1995; Malhi *et al.*, 1995b, 2004b; Pilbeam, 1996) observed that there was more recovery of ^{15}N fertilizer in the crop under humid or subhumid environments, whereas the recovery of ^{15}N fertilizer was more in the soil under dry or semiarid environments. This poor plant NUE and higher accumulation of NO_3^--N in soil increase the potential for nitrate-N leaching from applied N (Sardas, 2002).

Under water-scarcity conditions, application of N helps enhance both WUE and NUE. Kmoch *et al.* (1957) showed that N application enhanced total water use, as well as the depth of water extraction by winter wheat. Compared with the unfertilized crop, Brown (1971) and Bond *et al.* (1971) reported increased water use by N-fertilized winter wheat as well as spring wheat. Heitholt (1989) found that optimum N supply, as reflected by leaf N concentrations, promoted higher WUE in drought-stressed wheat in the southern Great Plains of the United States. In a similar study with a dryland corn–wheat rotation in Punjab, a 80-kg N ha^{-1} application to wheat slightly changed the water extraction from 0 to 90 cm, but resulted in almost a 100%

greater water extraction from the 90- to 180-cm soil layer compared with the unfertilized crop (Singh *et al.*, 1975). Better rooting and accelerated root extension into deeper layers and greater use of soil-stored water due to applied N have been observed in a number of studies from several countries (Gajri *et al.*, 1989; Prihar *et al.*, 2000). In fact, a yield goal with a given water supply could be achieved using various combinations of fertilizer N with available soil moisture at seeding and rainfall during vegetative and reproductive phases of crop development (Benbi *et al.*, 1993).

However, when precipitation is adequate and well distributed, the N supply could become the major factor in controlling yield (Stout *et al.*, 1988). Under such nonstressed conditions, WUE in wheat increased with increasing N up to 140 kg N ha^{-1} (Eck, 1988). For pearl millet production in West Africa, the addition of fertilizer increased soil water use over the control (Bationo *et al.*, 1993).

B. Fully and Partially Irrigated Environments

Irrigation water in certain regions may be plentiful and is used to meet the water requirements of crops, whereas in others it may be unable to meet total crop needs. Under both situations, N and water have been shown to exhibit strong synergistic interactions with respect to crop yield, yield components, NUE, WUE, and environmental impacts.

Under constrained irrigation resources, small supplemental irrigation at a crucial growth stage could substantially improve crop yield and NUE. Several ^{15}N-labeled and other studies have shown that irrigation could significantly increase the recovery of applied N in grain and straw at harvest, ranging from 10% in wetter years to over 60% in drier years (Garabet *et al.*, 1998; Geesing *et al.*, 2001; Hartman and Nyborg, 1989). Prihar *et al.* (1989) observed that 85% of the variations in dryland wheat yield could be explained by water supply and applied N. Whitfield and Smith (1992) reported a NUE of 20.7 kg wheat grain kg^{-1} N with the application of 150 kg N ha^{-1} under irrigation compared to a NUE of −5 to 1.5 kg grain kg^{-1} N with an application of 150 kg N ha^{-1} without irrigation. In a study in Victoria, Australia, irrigated canola accumulated 35 kg N ha^{-1} more than without irrigation in one of two years (Taylor *et al.*, 1991). In Punjab, with a water supply of 300 and 450 mm, an application of 80 kg N ha^{-1} increased the 4-year averaged wheat yield from 2.2 and 2.7 tons ha^{-1} without N to 3.0 and 4.5 tons ha^{-1}, respectively (Prihar *et al.*, 1981). In Egypt, rapeseed receiving irrigation at 18- to 22- and 29- to 30-day intervals had seed yield increases by 29.5 and 10.9%, respectively, over those irrigated at a 41-day interval (Shahin *et al.*, 2000). Thus, a simultaneous increase in water and N supply produced remarkably higher yields than those obtained with water and N alone.

For achieving maximum NUE and WUE, applications of water and fertilizer should be in concert to minimize NO_3^--N losses from the soil profile and to maximize uptake by the crop. For example, on a low-water retentive porous sandy loam soil, Chaudhary and Bhatnagar (1977) obtained a maximum wheat yield with 150 kg N ha^{-1} applied in three splits in combination with 360 mm water applied in seven splits. In contrast, the yield was lowest with full application of N at seeding and 360 mm water supplied in four splits. Thus, instead of fewer large applications, small but frequent irrigations often show higher benefits both in terms of crop production and WUE (Saini *et al.*, 1989) and reducing leaching of the nitrate (Singh and Sekhon, 1976). Similarly, a number of field studies have shown that fertilizer N interacts strongly with levels of irrigation for crop yield and WUE (Prihar *et al.*, 2000; Rao *et al.*, 1991). Gajri *et al.* (1993) showed low WUE with high irrigation at no-N, as well as with high N at zero irrigation, indicating that the crop suffered from N and water stress, respectively. Highest WUE obtained at intermediate irrigation and N rates suggest that both inputs should be at optimum rates.

Furthermore, the irrigation schedule for crops must consider available water storage in the potential root zone and distribution of rainfall. It is, therefore, necessary to optimize allocation of the available water supply among various periods of crop growth. Using their method based on equi-marginal productivity, Sandhu *et al.* (2000) demonstrated that fertilizer N and water could play a substitutional role for each other to achieve a medium yield target (Fig. 8). For example, under a water supply of 350 mm, 90 kg fertilizer N ha^{-1} is required to achieve a wheat grain yield target of 5 tons ha^{-1}. An additional 50-mm water supply reduces the N requirement to 40 kg N ha^{-1} for the same yield target. However, there are very few options for obtaining high wheat grain yield targets of 6 tons ha^{-1}, which require high amounts of both fertilizer N and irrigation.

Balanced use of N and P could further improve WUE. In a study on Loess slope farmland of China, combined application of N and P in the ratio of 3:1 resulted in the highest synergistic interaction in increasing soybean yield by 87 to 470% and WUE by 70 to 438% over their individual applications (Chen *et al.*, 2003). Another study in China showed that N and P fertilization promoted the growth of a wheat root system, leading to increased WUE (Zhang and Liu, 1993).

Irrigation practices that encourage utilization of soil-stored water also decrease deep-drainage losses of water and nutrients. Hoogenboom *et al.* (1987) obtained a deeper and more prolific rooting pattern of soybean by withholding irrigation. However, withholding early irrigation could be more detrimental to root proliferation and more so on coarse textured soils that dry faster and develop greater mechanical resistance (Prihar *et al.*, 2000). Under such conditions, water added a few weeks after seeding not only

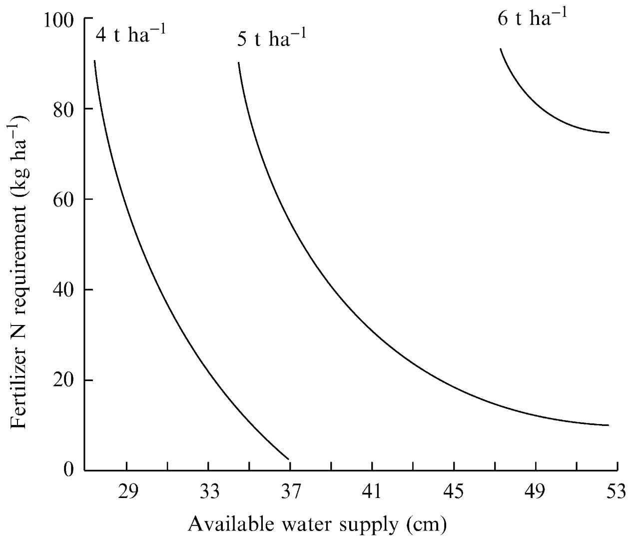

Figure 8 Wheat yield isoquants for computing optimal fertilizer N and available water supply to obtain targeted 4, 5, and 6 tons grain ha^{-1}. Adapted from Sandhu *et al.* (2000).

becomes available to the crop itself, but also has a priming effect on the use of soil-stored water and nutrients. Clarke *et al.* (2001) also confirmed these findings in their study with sandy loam soil in Berkshire, United Kingdom, where applying water to winter wheat at very early growth in the spring encouraged canopy development and improved both N recovery and grain yield. Similarly, in China, the effect of limited irrigation on wheat yield and NUE was highest at the jointing stage, followed by booting, tillering, and grain-filling stage in decreasing order (Deng, 2002).

In addition to the seasonal water supply, water retentivity of soil and optimal N supply determine the NUE. For instance, the NUE was lower on less water-retentive loamy sand soil than on sandy loam soil (Table X). At 80 kg N ha^{-1}, NUE increased with an increase in irrigation up to 200 mm. With 120 kg N ha^{-1}, the NUE did not increase with increasing irrigation from 50 to 125 mm, but increased remarkably when irrigation was further increased to 200 mm. With 40 kg N ha^{-1}, NUE at 200 mm irrigation was lower than that at 125 mm. The modeling analysis further revealed that clay soil is more productive than sandy soil in terms of grain yield, WUE, and NUE in the high and medium rainfall zone due to the low nitrate-leaching potential and water retentivity of clay soil (Asseng *et al.*, 2001).

Irrigation also helps improve the NUE by placing the fertilizer N in the appropriate soil zone where it is less prone to NH_3 volatilization losses and is accessible to the growing roots. For example, application of urea-N before

Table X
NUE in Wheat (kg Grain kg^{-1} N) as Affected by Application of Fertilizer N and Water in Different Combinations on Two Soils[a]

Number of irrigations	Total irrigation water added (mm)	Rate of N (kg N ha^{-1})		
		40	80	120
Loamy sand				
0	0	5.3	4.8	0.9
1	50	23.3	12.0	9.8
2	125	23.0	17.6	8.8
3	200	19.5	20.0	14.8
Sandy loam				
0	0	8.5	5.5	1.5
1	50	20.2	18.4	17.8
2	125	33.2	25.5	17.0
3	200	30.2	30.3	23.7

[a]Adapted from Gajri *et al.* (1993).

preseeding irrigation has been found to be superior to drilling of N at seeding in wheat (Sandhu and Sidhu, 1996). In their study with sandy loam soil, 39% of the fertilizer N applied before preseeding irrigation was located in the 20- to 60-cm layer after irrigation, which, being in the moist zone for a longer period, (a) enhanced its absorption by the plant roots, (b) supported root growth in deeper soil layers, and (c) minimized NH_3 volatilization. The ^{15}N-labeled studies of Malhi (1995) and Malhi *et al.* (1996) confirmed pronounced improvement in the plant recovery of broadcast urea-N on ZT soil or on perennial grassland soil when it was followed by an immediate water supply. Similarly, the controlled N × water interaction field study of Hartman and Nyborg (1989) confirmed that band placement of urea-N into the subsoil was much superior than surface broadcast-incorporated N in enhancing crop yields and plant recovery of applied ^{15}N, as well as in reducing N immobilization in soil, especially under drought conditions.

The foregoing discussion reveals that both NUE and WUE are interdependent and that the efficiency of one input is influenced by the adequacy of the other; their optimal use can ensure great benefits due to a synergistic N × water interaction. However, application of N should be reduced under a limited availability of soil moisture because excessive N produces vigorous vegetative growth, resulting in greater water loss via transpiration (Kappen *et al.*, 2000), leading to a water deficit (Herwaarden *et al.*, 1998). However, the excessive irrigation frequency may increase grain yield but could decrease grain quality (Gill and Singh, 1999). Also, application of excessive N accompanied by heavy irrigations, as in rice crops, can cause NO_3^--N to move below the rooting zone and ultimately reach groundwater (Aulakh *et al.*,

2000) and enhance denitrification losses and emission of N_2O (Aulakh *et al.*, 2001b) and CH_4 (Aulakh *et al.*, 2001c). In other crops such as wheat, super optimal rates of fertilizer N and irrigation could produce excessive vegetative growth without any benefit to grain yield (Parihar and Tripathi, 1989).

The review of literature thus revealed that high yields, NUE, and WUE could be sustained with minimal N losses by split applications of fertilizer, combined with an appropriate irrigation schedule, to ensure absorption of N from a deep soil profile by plant roots.

VIII. EFFECTS ON CARBON STORAGE AND SEQUESTRATION IN SOIL

The sustainability of agricultural production is linked to soil quality, which in turn is a function of SOM. Organic matter improves soil tilth, biological activity and diversity, aids air and water movement, promotes water retention, and reduces soil erosion, in addition to influencing pesticide efficacy and its decomposition process. Soil organic C (SOC) is an index of SOM, which is the major source of plant nutrients. Cultivation practices cause a substantial decrease in total organic C in soil (Malhi *et al.*, 2003a; McGill *et al.*, 1988), which may be contributing over time to the increased levels of atmospheric CO_2 causing global warming. The maintenance of SOC at existing levels or its enhancement by sequestering C is important in sustaining and improving the soil quality and productivity and in ameliorating the greenhouse effect. Carbon sequestration occurs when a given set of management practices lead to a positive balance in the flow of C to soil (Izaurralde *et al.*, 1998). Improved NUE as a result of other management practices, including the interaction of N with other nutrients, as discussed in preceding sections, could influence the storage of SOC. The effects of NUE are expected to be greatly different in temperate regions than in tropical and subtropical regions, as temperature is the predominant singular factor controlling the rate of mineralization of SOM, the discussion is thus presented accordingly.

A. Temperate Regions

In temperate regions, where mineralization of SOM is slow and crop residues are generally returned to the soil, long-term applications of N to annual crops have often shown a considerable increase in SOC. The total organic C (TOC) after 10 years of N fertilization in barley in soil was increased significantly (Nyborg *et al.*, 1995b; Solberg *et al.*, 1997). Crop residues, including roots, are the primary source of organic materials added to the soil in many cropping systems. The increase in TOC in 0- to 15-cm soil was linearly ($R^2 = 0.76$*; $p \leq 0.05$) related to the amount of C returned to the soil in crop residues, which was associated with the increase in crop yield with N fertilization (Nyborg *et al.*, 1995a). For example, in this study, seed yields of barley were 898, 2092, 1085, and 2643 kg ha^{-1}, respectively, in the no-N ZT, surface-broadcast 56-kg N ha^{-1} ZT, no-N CT, and broadcast-incorporated 56-kg N ha^{-1} CT treatments. The corresponding values for TOC were 32.1, 42.0, 28.7, and 34.5 tons C ha^{-1}, and for total N (TN) were 2.77, 3.74, 2.51, and 3.01 tons N ha^{-1}, respectively. The increase in TOC was 14% after 18 years of continuous wheat (Janzen, 1987), and the cropping systems comprising wheat, fallow, flax, lentil, rye (*Secale cereale* L.), and perennial forages showed an increase of 2.8 to 9.5 tons TOC ha^{-1} (Campbell *et al.*, 2000). These observations are further supported by the presence of higher SOC in cropping systems that included forages in 4 of 9 years (Angers *et al.*, 1999) and that were under long-term ZT management (Campbell *et al.*, 2001; Dormaar and Carefoot, 1998). While evaluating the effects of 35 years of different cropping systems, Gregorich *et al.* (2001) observed that soils under corn monoculture cropping had about 70–80% less C than those under continuous grass; however, the effect of fertilizer application on the enrichment of SOC by about 6 tons C ha^{-1} was observed only under the corn monoculture.

In a 10-year tillage and N management experiment in Kansas, Matowo *et al.* (1999) found that concentrations of SOC increased with an increasing rate of N fertilizer application to sorghum under both ZT and CT systems, with the largest increases of 14.5 to 19.2 g kg^{-1} soil in the surface 0- to 2.5-cm layer. They demonstrated that SOC in different soil depths could be influenced by the N source, rate, and method of placement. As most of the biologically related characteristics are generally SOC driven, enhanced accumulation of SOC is often associated with a proportionately increased size of labile pools of microbial biomass C, light fraction organic C (LFOC), microbial biomass N, and hydrolyzable and potentially mineralizable N. A study by McCarty and Meisinger (1997) in the United States showed that the application of fertilizer at 135 kg N ha^{-1} caused a substantial increase in TOC, TN, biomass N, and active N in ZT soils compared to the no-N control. While the application of fertilizer N at an excessive rate of 270 kg N ha^{-1} tended to suppress biologically active N pools, it had no detrimental impact on TN or TOC, suggesting that adequate fertilizer application and other management practices can improve soil quality. Similarly, studies in Georgia suggested that SOC and organic N could be conserved and aggregation of soil improved by sequestering atmospheric CO_2 and N_2 into the soil by using ZT with cover crops and N fertilization (Sainju *et al.*, 2001, 2003). While SOC, TN, microbial biomass C, and LFOC remained unaffected in unfertilized long-term ZT management, these parameters showed positive responses to fertilization (Campbell *et al*., 2001).

Research on perennial forages has shown that C and N sequestration in soil is influenced by the rate and source of N fertilizer application (Baron, 2001; Malhi *et al*., 2002b, 2003c,d; Mensah *et al*., 2003). With the addition of N fertilizer at 168 kg N ha^{-1}, the ability of perennial forages to sequester C in soil was increased by about 50% from 50.3 g C kg^{-1} soil in the no-N control to 75.5-g C kg^{-1} soil (Malhi *et al*., 1997b). On a Solonetzic soil where different rates of N were applied to smooth bromegrass, the amount of TOC and TN increased with the N fertilization rate (McAndrew and Malhi, 1992). Among different N sources used in their study, urea produced the smallest increase in TOC, whereas the largest increase was realized with ammonium nitrate. Studies in Saskatchewan have shown that the addition of N and S to a grass forage stand substantially increased DM yield, TOC, and levels of LFOC compared to the no-N control (Nyborg *et al*., 1997, 1999). In these experiments, forage DM, NUE, TOC, and TN all increased substantially with N + S treatment after 13 years, but the value of these parameters decreased in the N-only treatment because of a nutrient imbalance (Malhi *et al*., 2004d). For example, mean annual forage dry matter yields were 1.33, 1.12, and 4.84 tons ha^{-1} in the unfertilized control, N alone, and N + S treatments, respectively. The corresponding values for TOC in the 0- to 37.5-cm soil were 183.4, 170.4, and 202.3 tons C ha^{-1}. The optimum amounts of forage yield, TOC, and TN with a combined application of N and S illustrate the importance of balanced nutrition of crops. In a grassland study in Alberta, Canada, the mass of TOC and LFOC in surface and subsurface layers increased with the N rate (Table XI). While the maximum mass of TOC in the soil profile (130 tons C ha^{-1}) was observed at 224 kg N ha^{-1}, the maximum gain in the mass of TOC with each kilogram of applied N (10.9 kg C kg^{-1} N) was at the lowest rate of 56 kg ha^{-1} of applied N and had the lowest gain in TOC (3.0 kg C kg^{-1} N) at the highest rate of 336 kg N ha^{-1} (Malhi *et al*., 2003d). In this experiment, the annual average hay yield increased from 1.41 tons ha^{-1} in the no-N control to 5.82 tons ha^{-1} with 224 kg N ha^{-1}. Because most of the aboveground portion of bromegrass was removed as hay, the increase in TOC and LFOC in soil was mainly associated with the increased root biomass of forage grasses in response to N fertilization (Lorenz, 1977; Malhi and Gill, 2002b) and possibly some biomass of fallen dead leaves. These studies suggest that when aboveground bromegrass production is increased with proper fertilization, the corresponding increase in root biomass contributes to sequester more SOC. The preceding discussion indicates that fertilizer N is more effective on grasslands managed as hay than cereal cropping systems, most likely due to a greater production of root biomass by forage grasses and a reduction in tillage frequency compared to cereals.

Table XI
Mass of Total Organic C and Light Fraction Organic C after 27 Annual Applications of Six N Rates to Bromegrass Grown as Hay on a Thin Black Chernozemic Soil in Alberta, Canada[a]

	Annual rates of N (kg N ha^{-1} $year^{-1}$)						
Soil depth (cm)	0	56	112	168	224	336	SEM[b]
Total organic C mass in soil (tons C ha^{-1})							
0–5	21.2	25.8	28.3	31.3	32.4	33.2	1.2***
5–10	18.1	20.4	20.2	20.7	21.2	20.3	0.6*
10–15	15.3	17.0	17.6	18.1	20.2	17.0	0.9*
15–30	33.5	41.5	46.1	45.0	56.0	44.2	3.8*
Sum	88.1	104.7	112.1	115.2	129.9	114.7	4.6***
Light fraction organic C mass in soil (tons C ha^{-1})							
0–5	1.74	4.14	7.83	11.87	13.87	13.10	0.75***
5–10	0.73	1.38	1.53	2.05	2.44	2.70	0.11***
10–15	0.50	1.01	1.11	1.02	1.27	1.28	0.08***
15–30	0.74	1.64	2.21	1.68	2.22	1.62	0.25***
Sum	3.71	8.18	12.68	16.62	19.80	18.70	0.84***

[a]Modified from Malhi *et al.* (2003d).
[b]Standard error of means.
*$p \leq 0.05$.
***$p \leq 0.001$.

B. Tropical and Subtropical Regions

Under tropical and subtropical climate, the mineralization of SOM is accelerated by the prevailing high temperature. Moreover, crop residues are generally removed from the field, especially in developing countries, to use them for other purposes or are burned to facilitate fast and easy land preparation. The literature is replete from several countries of these regions that applications of N alone or in combination with P and K do not show pronounced effects on SOC in field crops; SOC is slightly decreased (Aoyama and Kumakura, 2001; Belay *et al.*, 2002; Kapkiyai *et al.*, 1999; Yadav, 1998), maintained due to a quasi-equilibrium established between mineralization and added C through root biomass (Aulakh *et al.*, 2001a; Roy *et al.*, 2001), or shows a small increase over a prolonged period (Benbi and Biswas, 1997; Bhatnagar *et al.*, 1994). For example, in a long-term experiment with an annual corn–wheat–forage cowpea-cropping sequence in Punjab, India, application of N alone or in combination with optimal P and K for 22 years exhibited a small change in SOC (Fig. 9). However, application of FYM in conjunction with optimum NPK increased SOC from 2.0 g kg^{-1} soil at the start of the experiment to 4.2 g kg^{-1} soil, along with a proportionate increase in alkaline $KMNO_4$-extractable N (potentially

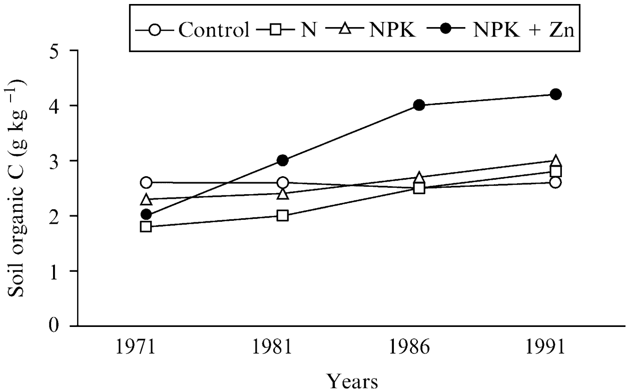

Figure 9 Changes in soil organic carbon in the surface 0- to 15-cm layer of semiarid soil in the subtropics under different fertilizer treatments to annual corn–wheat–forage cowpea for 22 years. Drawn with data from Benbi and Biswas (1997).

available N) from 105 to 134 kg N ha^{-1} (Benbi and Biswas, 1997). Similarly, SOC increased from 3.6 to 6.1 g kg^{-1} soil in a short period of 2 years when organic materials and NPK were applied together (Kumar *et al.*, 2000). In a field study with a corn–wheat rotation in Rajasthan, India, fertilizer application at 120 kg N and 17.5 kg P ha^{-1} gave the highest grain yield and showed an increase in SOC from 2.1-g kg^{-1} soil in the unfertilized control to 3.3-g kg^{-1} soil after 11 years (Bhatnagar *et al.*, 1994).

In fact, several studies have shown that a long-term application of N alone usually decreases SOC, whereas applications of P and K along with N minimize the depletion of C from soil and tend to stabilize or enhance SOC (Gangaiah and Prasad, 1999; Kumar and Yadav, 2001; Sharma and Subehia, 2003; Tolanur and Badanur, 2003). In a long-term experiment with annual fertilization to a wheat–corn rotation from 1982 to 2000 on a calcareous sandy loam soil under irrigation in China, the concentration and mass of TOC and TN increased with a balanced fertilization of N, P, and K as compared to an unfertilized control and was maximized when all nutrients were applied together (S. Yang, personal communication). For example, the mass of TOC in the 0- to 20-cm soil was 19.6, 20.2, 20.9, and 21.4 tons ha^{-1}, respectively, in the unfertilized control, N, NP, and NPK treatments. In this study, the corresponding mean seed yields obtained in these treatments were 3430, 4886, 6995, and 7509 kg ha^{-1}, respectively (Yang *et al.*, 2004). This suggests a close relation between SOC and crop yield increase from balanced fertilizers applications.

The situation could be markedly different when crop residue or stubbles are incorporated into soil after crop harvest. For example, in a 59-year experiment with sugarcane in South Africa, SOM in the surface 10-cm soil increased with increasing inputs of crop residues along with annual NPK fertilizer applications (Graham *et al.*, 2002). Similarly, SOC was substantially improved with the application of NPK + FYM to potato-based cropping (Roy *et al.*, 2001). In the humid ecosystem at Kalyani, India, an integrated nutrient supply through inorganic and organic sources to a rice–wheat system (where soil remained submerged during the rice-growing period) had pronounced effects on SOC (Hegde, 1998). In a 4-year study with an annual rice–wheat rotation in the semiarid subtropical climate, fertilizer N and P had no effect on SOC, but green manure application resulted in significantly higher SOC concentrations (Table XII). The incorporation of wheat or rice residue accentuated SOC deposition and reduced soil bulk density. These results exhibited a positive relationship of NUE with SOC ($r = 0.66, p \leq 0.05$) and an inverse relationship of SOC with soil bulk density ($r = -0.94$, $p \leq 0.01$). Such improvements in soil physical conditions (decreased bulk density and resultant improved water infiltration rates and soil structure) and increased SOC play an important role in the wheat crop following the puddle rice culture in a rice–wheat cropping system for establishing seedlings and also because wheat, unlike rice, is a deep-rooted crop.

Few reports are available from subtropical and tropical regions that indicate that when ZT management is adopted, it could further enhance SOC. For instance, in a long-term experiment with 17 consecutive crops of corn in

Table XII

Effect of Integrated Use of Fertilizer Urea N (FN), Green Manure (GM), Wheat Residues (WR), and Rice Residues (RR) on Rice Yield, Nitrogen Use Efficiency, Soil Bulk Density, and Carbon Sequestration in Rice–Wheat System in Subtropics[a]

Treatment[b]		Rice yield[c]	NUE	Soil bulk density[d]	SOC[d]
Rice	Wheat	(tons ha^{-1})	(kg rice grain kg^{-1} N)	(g cm^{-3})	(g kg^{-1})
Control		3.40	—	1.60	3.74
120 kg FN ha^{-1}	120 kg FN ha^{-1}	5.62	18.5	1.60	3.71
GM_{20} + 32 kg FN ha^{-1}[e]	120 kg FN ha^{-1}	5.85	20.4	1.54	4.05
WR_6[f] + GM_{20} + 32 kg FN ha^{-1}	120 kg FN ha^{-1}	5.92	21.0	1.50	4.92
120 kg FN ha^{-1}	RR_6[f] + 120 kg FN ha^{-1}	5.63	18.6	1.54	4.33
$LSD_{0.05}$		0.24		0.05	0.22

[a]Modified from Aulakh *et al.* (2001a).
[b]Basal P was applied in all treatments to both rice and wheat.
[c]Three-year (year, 2–4 of the experiment) mean yields.
[d]Measured at the end of 4-year experiment.
[e]Amount of 120 N kg ha^{-1} applied through 20 tons GM and the balance through fertilizer N.
[f]Wheat residues (WR) and rice residues (RR) applied at 6 tons ha^{-1}.

western Nigeria, the mean SOC was 18.6 g kg^{-1} soil under ZT as compared to 12.2-g kg^{-1} soil in CT (Lal, 1998). Moreover, the impact was much higher when recommended fertilizers were applied and crop residues retained. These results show that the regular input of crop residues along with inorganic fertilizers improve soil quality and more so in ZT management.

In a rice monoculture, where soil remains submerged for the whole year, a higher accumulation of SOC is frequently observed due to slower decomposition under anaerobic conditions (Cassman *et al*., 1996; Sahoo *et al*., 1998). In an 8-year annual rice–rice sequence experiment at Hyderabad, India, application of fertilizers at a recommended dose of 120 kg N, 26 kg P, and 33 kg K ha^{-1} increased SOC from 4.9 g kg^{-1} soil in the unfertilized control to 7.3 g kg^{-1} soil (Mohammad, 1999). Similarly, in a 2-year period, the soil under a rice–rice cropping system in Philippines accumulated 2736 kg C ha^{-1} as compared to only 457 kg C ha^{-1} in a corn–rice system (Witt *et al*., 2000).

In summary, adequate and balanced fertilization can be used to improve SOC in soil by sequestering more atmospheric C. The increase in organic C concentrations in soil is influenced by N rate, source, application time, and placement method. The majority of the C storage in soil occurs in the surface layers, and increasing the duration under ZT management causes the thickness of C stratification to increase. The change in LFOC, a potential soil quality indicator, is more responsive and sensitive to N application than TOC. Perennial forages can sequester more C in soil than cultivated annual crops because of elimination of tillage. The increased C storage in soil from N application is due to an increase in aboveground crop residue production and root biomass induced by fertilization, and resultant residue C input to the soil, thereby sustaining or improving the fertility, quality, and health of the soil. In subtropical and tropical regions, despite the fast decomposition of SOM, proper management of NPK nutrients can maintain soil fertility by reducing the depletion of C from soil and increasing C sequestration rates. It appears that adoption of ZT management, increased use of balanced fertilization from inorganic and organic sources, and retention of crop residues would increase SOC storage in agricultural lands in the future.

IX. NITROGEN LOSSES AND TRENDS OF FERTILIZER CONSUMPTION

A. Nitrogen Losses and Use Efficiency

Recovery of applied N by crops under field conditions ranges from 25 to 34% for rice and 40 to 60% for other crops, with global average value of about 50% (Mosier, 2002). The unutilized N may remain in soil in various forms and/or get lost through several processes, including NH_3 volatilization, denitrification, and nitrate leaching, and the literature is replete with such evidence (Aulakh, 1994; Aulakh *et al.*, 1992; Goulding, 2004; Keeney, 1982). Nevertheless, a brief mention of the fate of N in applied fertilizers is made in this review. An example of how fertilizer NUE decreases as N in excess of that needed for economic rates of crop production is shown by a study conducted by Broadbent and Carlton (1979). Their results and synthesis of the results by Legg and Meisinger (1982) revealed that maximum NUE was found at the same fertilizer N rate needed to obtain maximum corn yield. When N was applied in excess of this amount, large amounts of NO_3^- accumulated in the soil profile, which were susceptible to denitrification and leaching. Residual NO_3^- in the soil profile could be leached with irrigation water. High rates of leaching and nitrification in permeable or porous soils and relatively high fertilizer N rates combine to make NO_3^- leaching a serious problem in many irrigated soils (Aulakh *et al.*, 2000). In intensively cultivated semiarid subtropical region of Punjab, where average fertilizer N consumption increased from 56 to 188 kg N ha^{-1} year^{-1} during 1975 to 1988, NO_3^--N concentration in the shallow well waters increased by almost 2 mg liter^{-1} (Aulakh and Bijay-Singh, 1997). The NO_3^- concentration of the Santa Ana River of California increased from an average of 2 mg liter^{-1} in 1930 to about 6 mg liter^{-1} in 1969 (Ayers, 1978). In Nebraska, NO_3^--N of groundwater increased, on average, from 2.3 mg liter^{-1} in 1961 to 3.1 mg liter^{-1} in 1971 while fertilizer N use quadrupled and irrigation increased 50% (Muir *et al.*, 1973). Thus, fertilizer N in excess of crop potential utilization leads to losses to the environment; obviously, considerable room for improving management to decrease losses exists.

B. Global Consumption of N, P, and K Fertilizers

In addition to N losses, excessive N application can lead to a decline in crop production through deficiencies of macro- and micronutrients in production systems. The foregoing subsections revealed that NUE could be improved by the optimum and balanced use of different plant nutrients. Among these, the majority of N, P, and K is supplied by synthetic fertilizers. Since 1960–1961, global synthetic N-fertilizer consumption has increased from 10.8 to 82.8 Tg (1 Tg = 10^{12}g) N in 2001–2002 (IFA, 2003). The corresponding increase in the consumption of P and K fertilizers was from 4.7 to 14.6 Tg P and 7.0 to 18.7 Tg K (IFA, 2003). There is no doubt that these fertilizers have contributed significantly to continuing increases in grain production to meet the increasing demands of both human and livestock population. However, the global distribution of fertilizers has changed markedly in the past few decades. While N, P, and K fertilizer use, as well as

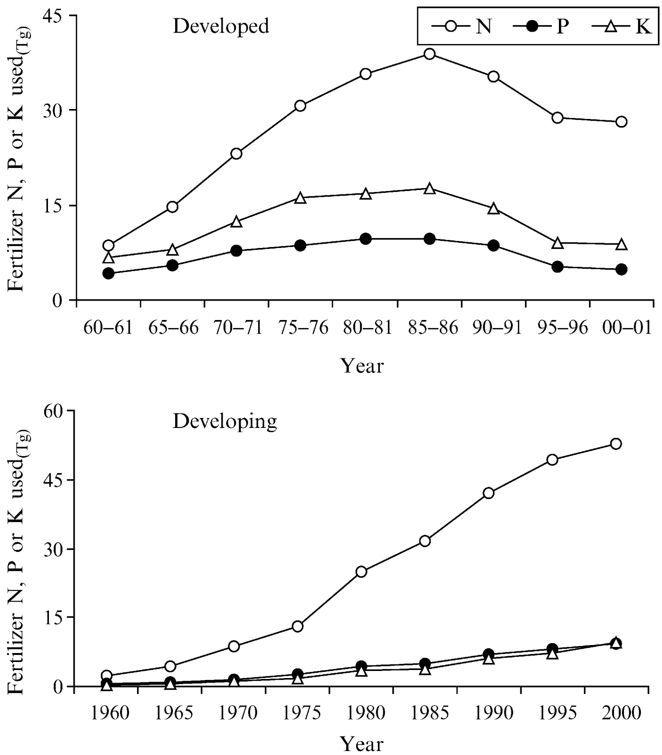

Figure 10 Fertilizer N, P, and K consumption in developed and developing parts of the world. Drawn with data from IFA (2003).

grain production, has declined in developed countries since 1985, they have continued to increase linearly in the developing world, although at different rates, over the past three decades (Fig. 10). Nitrogen is used in optimum and even excessive amounts, whereas P and K are not always supplemented adequately (Aulakh and Bahl, 2001; Ma, 1977; Mosier, 2002; Zhu, 1997).

C. P/N AND K/N RATIOS OF CROPS AND APPLIED FERTILIZERS

A balanced and judicious use of fertilizers is the key to efficient nutrient use and for maintaining soil productivity. Balanced fertilization requires an optimum input of N, P, and K in the ratios needed to maintain soil fertility to optimize crop productivity and to minimize N losses. The main cereal crops, such as wheat, rice, and corn, typically have P/N ratios in both grain and straw in the narrow range of 0.15–0.24 (Fig. 11). Oilseeds such as

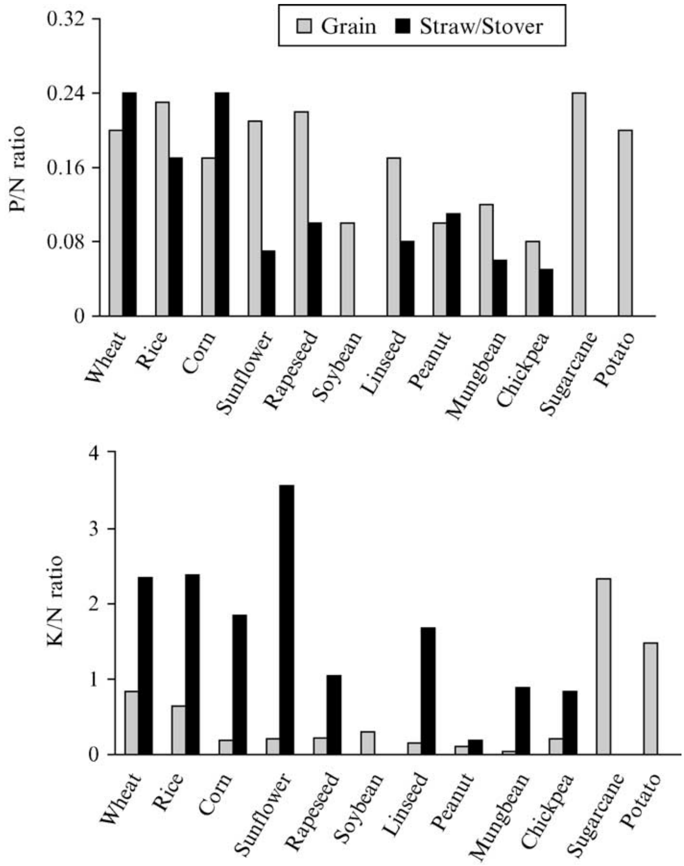

Figure 11 P/N and K/N ratios of common cereals, oilseeds, pulses, and other crops. Note that in the case of sugarcane and potato, data are for canes and tubers, respectively. Drawn with data from TFI (1982) and Aulakh and Bahl (2001).

sunflower, rapeseed, and linseed/flax (*Linum usitatisimum* L.) have similar P/N ratios in seed, but are much lower in straw (0.07–0.10). Legumes such as soybean, peanut, and mungbean grain have relatively lower P/N ratios (0.05–0.12) because they accumulate high amounts of N through BNF. In case of sugarcane, the P/N ratio is 0.25. The K/N ratio of crop straw or stover is much higher than the P/N ratio in grains, respectively, ranging from 1.85–2.38 as compared to 0.19–0.84 in the grain of cereal crops, 1.05–3.57 as compared to 0.15–0.22 in oilseeds, and 0.19–0.89 as compared to 0.04–0.21 in legumes (Fig. 11). Potato tubers have a K/N ratio of 1.48 as compared to a P/N ratio of 0.20. According to the Fertilizer Institute, if P and N fertilization is required, these should be applied in a P/N ratio of

~0.15 (TFI, 1982). As K is also more susceptible to leaching than P, removal of K from the field is much more than P.

The ratio of global consumption of P/N in 1995 was 0.17 (0.39 P_2O_5/N) and K/N was 0.22 (0.26 K_2O/N) and has been predicted up to the year 2030 to remain relatively constant (Mosier, 2002). However, a large disparity in fertilizer consumption ratios exists within countries of a continent as well as among different continents (Table XIII). In North and Central America, the United States and Canada are using near optimum N and P but K

Table XIII
Consumption of Fertilizer N, P, and K Along with Their Ratios in Major Consuming Countries of Different Continents in 2000–2001 (FAO, 2003)

	Fertilizer N, P and K consumption				
Continent and country	N (000 ton: N)	P (000 ton: P)	K (000 ton: K)	P/N ratio	K/N ratio
North and Central America					
United States	10251.3	1663.4	3689.0	0.162	0.360
Canada	1554.4	267.9	256.8	0.172	0.165
Others	1347.3	137.7	145.5	0.102	0.108
South America					
Brazil	1999.3	1111.0	2398.2	0.556	1.200
Argentina	481.3	137.3	23.4	0.285	0.049
Others	906.4	170.1	64.1	0.188	0.071
Europe					
France	2316.0	347.2	858.1	0.150	0.371
Germany	1847.6	153.4	451.5	0.083	0.244
Spain	1113.7	248.1	388.0	0.223	0.348
UK	1030.0	124.0	315.4	0.120	0.306
Russian Fed	960.0	122.3	149.4	0.127	0.156
Others	5855.5	2862.1	1828.4	0.489	0.312
Asia					
China	22482.0	3671.1	2778.4	0.163	0.124
India	10920.2	1840.4	1300.8	0.169	0.119
Pakistan	2265.7	295.9	19.0	0.131	0.008
Malaysia	525.0	110.6	539.4	0.211	1.027
Japan	487.0	255.0	317.8	0.524	0.653
Others	9532.8	1534.3	1460.6	0.161	0.153
Oceania					
Australia	1002.2	478.9	168.1	0.478	0.168
New Zealand	242.0	200.0	114.5	0.826	0.473
Africa					
Egypt	1073.4	66.1	37.3	0.062	0.035
South Africa	411.0	95.2	107.1	0.232	0.260
Others	450.0	109.9	108.6	0.244	0.241
World	81624.5	14259.8	18386.5	0.175	0.225

consumption is suboptimal in Canada due to high K testing soils. In South America, Brazil is using well above optimal proportions of N, P, and K. In fact, the K/N ratio in Brazil is the highest in the world, as fertilizer N is used in relatively small amounts for the predominantly grown soybean crop. On the other side, all other countries in this continent may need to enhance the use of K fertilizers. European countries show fewer variations in P/N and K/N ratios and are quite close to desirable levels except Germany, where the P/N ratio is very low (0.08), and Russia with the lowest K/N ratio of 0.16. Within Asia, China and India, which are the highest consumers of fertilizers in the world, perhaps need to use substantially more K. While Malaysia ranks second in the K/N ratio (1.03), Pakistan has the lowest K/N ratio of 0.008 in the world. In Africa, Egypt uses relatively low proportions of P and K fertilizers. Amazingly, where P/N ratios in different regions/countries vary 10-fold (0.083 to 0.826), K/N ratios (0.008 to 1.20) vary 150-fold. There appears to be a potential for imbalance in P and K fertilization in the future that may present problems for food production.

Regions where crop residues are not returned to the field and/or which have degraded soils, deficiencies in P and K may limit production and quality of crops, even though N may be applied in adequate or excessive amounts. For instance, in India and China, where almost 50% of the global N fertilizer is used, K/N ratios of 0.124 and 0.119 (Table XIII) are far below the K/N ratio removed by the crops (Fig. 11). However, these guiding ratios might not be applicable in all situations, as the need and use of N, P, and K fertilizers could vary with crops, soils, and management practices. For instance, legumes use only a small starter or pop-up dose of N and, therefore, fertilizer P/N and K/N ratios for these crops should be much higher than other crops. The depletion of K can be avoided to some extent by taking care to return all crop residues to the field. For soil supplying capability for K and management effects, a specific example of data from Punjab, the cradle of the Green Revolution in south Asia, is cited here. Punjab, a northwestern state covering only about 1.5% of the geographical area and producing about 11% of total food grains of India, contributes 64% wheat and 42% rice in the national food pool. Despite intensive cropping and high productivity, the use of fertilizer K in Punjab is almost negligible (0.04 K/N). However, its removal by crops is 19% greater than that of N. Mining of soil K has progressively increased from 132,000 tons in 1960–1961 to 683,000 tons in 1998–1999, and the present K balance is negative (Aulakh and Bahl, 2001). Apparently the negative K balance has not affected crop productivity, which appears to be stabilized around 16 kg food grains kg^{-1} nutrient used as compared to only 8 kg food grains kg^{-1} nutrient at the India level. This is due to the sufficient release of available K from the K-rich illitic alluvial soils and the return of K to the soil by burning 70% of K-rich rice straw in the field (Aulakh and Bahl, 2001). History reveals that in the early sixties, when fertilizer responsive high-yielding crop cultivars were introduced, optimum yields could be obtained with the application of fertilizer N only. However, the bumper harvests soon depleted other nutrients and within a few years P deficiency appeared in a big way. This was followed by a deficiency of Zn, and application of Zn with the adequate dose of N, P, and K enhanced the N recovery and NUE by crops in such intensively cropped soils (Benbi and Biswas, 1997). As crop demand for K increases with larger N and P applications and the reserves of soil K are being depleted faster, future long-term high productivity cannot be maintained in such systems if balanced fertilization is not practiced.

X. CONCLUSIONS AND FUTURE RESEARCH NEEDS

The global distribution of fertilizer use has changed markedly in the past few decades. While N, P, and K fertilizer use has declined in developed countries since 1985, it has continued to increase in the developing world at linear rates. During the past five decades, the role of fertilizer N in augmenting food grain production has been widely recognized in both the developed and the developing world. The experience of the past half-century has revealed that fertilizers are the kingpins of the green revolution and are the best hope for meeting food challenges in the future. Even though agricultural production has increased dramatically, along with a matching increase in the consumption of fertilizer N, the NUE remains relatively low, with a global average of about 50%. The inefficient use of fertilizer N in most parts of the world has led to losses of unutilized N to the environment through leaching and gaseous emissions. Thus, increasing NUE remains a clear goal for maintaining food production while avoiding excessive N use and undesirable environmental pollution.

In most of the regions, N is used in optimum and even excessive amounts, while P and K are not always supplemented adequately. The ratios of global consumption of P/N and K/N are 0.17 and 0.22, respectively, and have been predicted to remain relatively constant for the next 3 decades. However, a large disparity exists in fertilizer consumption ratios within countries of a continent as well as among continents.

The synergistic N $\times$ P interaction is responsible for a sizable yield gain leading to considerable improvements in both NUE and PUE. Most of the studies reported from several regions pointed out that crop responses to applied N level off earlier, whereas a synergistic response to N + P enables the crop to produce markedly higher yields. Higher levels of N are thus only effective when combined with higher rates of P. Similarly, applied N enhances the crop response to increasing levels of P, and consequently the quadratic response to varying rates of applied P could continue to be linear up to higher rates of P. In situations where farmers cannot afford to apply both N and P in optimum amounts, it would be better to apply smaller amounts of both N and P instead of large amount of N alone. Studies on the N × P interaction have helped to understand and interpret the complex effects of field management and to identify approaches in different ecosystems to enhance the benefits and to develop new strategies. For instance, synergistic interactions between N and P have helped explain the effect their banding has on root growth and proliferation and also on the development of appropriate N + P fertilizer combinations.

Significant N × K and N × P × K interactions could be expected where higher doses of N are used to increase crop production. These interactions are strongly positive and profitable at high levels of crop productivity in crops having high K requirements. Hence, exploiting the N × K and N × P × K interactions could remarkably increase the efficiency of applied N. The split application of N and K is used increasingly in fertilizer practices, which helps in creating a better interaction of K with N, particularly in situations where farmers are using low amounts of N. The precaution, however, is needed to synchronize the application of N and K at the most N-demanding plant growth stages. Such a practice would be highly beneficial in coarse-textured porous soils.

The N × S interaction studies indicated that a maximum crop yield is only attained when the two nutrients are provided in a balanced way, and correct diagnosis of nutrient deficiency is vital. If S deficiency is misdiagnosed as N deficiency and, as a consequence, additional N is applied, then the crop growth would be affected adversely and a greater yield and NUE penalty would result. A large number of reports suggest that N and S nutrition during the plant growth is highly desirable and their application at optimum rates is required to improve NUE and SUE, as well as to maintain oil content and fatty acid quality in oilseeds and protein concentration in most of the crops.

Information on N × Ca and N × Mg interactions is scanty and is mainly related to the positive effects of lime in acidic soils and gypsum in sodic/Solonetzic soils for correcting soil pH and improving plant growth. In certain situations, one or more micronutrients may become deficient, and their application is needed for optimum crop production and quality. While the N × Zn interaction is highly synergistic, numerous reports suggest that the N × Cu interaction could be either synergistic or antagonistic. The interaction of N with Fe, B, Co, and Mo is of great economic significance, especially in legumes, because these micronutrients are closely associated with one or the other step in the process of BNF.

Interaction of N with water plays an important role in root biomass production and growth, especially in the deeper soil layers, for extracting essential nutrients in both dryland and irrigated environments. The efficiency of both N and water is influenced greatly by the adequacy of each other, and their optimal use can ensure large benefits due to synergistic N × water and N × P × water interactions. In situations where irrigation water is plentiful, excessive irrigation must be avoided, as it could drastically decrease grain quality and enhance the downward movement of NO_3^--N below the rooting zone, ultimately reaching the groundwater. The best strategy for sustaining high yields, NUE, and WUE with minimal N losses would be splitting applications of fertilizers in a combination with an appropriate irrigation schedule in order to optimize absorption of N from the deep soil profile by plant roots.

Adequate and balanced fertilization plays a significant role in increasing the storage of organic C and N in soil to improve its fertility, quality, and health by sequestering atmospheric C. Most of the C stored in soil occurs in the surface layers and it increases with duration at a slow rate. The majority of total C stored in soil is in the light fraction organic matter, particularly under ZT and perennial grasslands, and LFOC (a potential soil quality indicator) is more responsive to N application than TOC. Perennial grasslands, even when hay is removed, sequester more C in soil than in cultivated annual crops. The increased C storage in soil from proper fertilization is due to an increase in the aboveground crop residue production and root biomass and the resultant residue C input to the soil. The amount of increase in SOC in soil is linked to the quantity of crop residues, and is associated with crop yield, nutrient uptake, efficiency, and recovery, which are influenced by N rate, source, time, and method of application. Even in subtropical and tropical regions where SOM decomposes much faster, proper management of NPK nutrients can maintain soil quality by reducing the loss of C from soil and increasing C sequestration rates. The literature suggests that adoption of ZT management, increased use of balanced fertilization from inorganic and organic nutrient sources, and returning of crop residues to soil would increase C storage in agricultural lands in the future.

The role of environmental factors and management practices in regulating NUE in field crops is now better understood. Nutrient interactions and availability of nutrients (e.g., Zn, Cu, Fe, and Mn) are regulated by a number of physical, chemical, and biological factors, such as pH, redox potential, temperature, soil organic matter, and water status in soils. Similarly, the nature and magnitude of interaction of N with other nutrients and water are determined by soil and crop type, level of available N and other nutrients in soil, rate of applied N and other nutrients, and climatic conditions. The effect of each individual parameter on crop growth, yield, and quality under controlled conditions is well established but their intertwined impacts often cannot be predicted with reasonable accuracy under field conditions.

During the past few decades, extensive information has become available on NUE in field crops, which has enhanced our understanding on the nature of interactions of N with other nutrients, processes involved, and their impacts under different environmental and agronomic settings. The "best management system" is not fixed but depends on the major limiting factors in each individual region, country, state, or farm. A synergistic interaction is entirely a bonus, being an outcome of the skillful balancing of nutrients. It adds to the returns and not to the cost, thus raising the benefit:cost ratio further.

Collectively, the benefits of improved use efficiency of N and other nutrients achieved by their balanced and optimum use include the following.

i. Reduction in the dose of N resulting in an economy of N to the farmers.
ii. Realizing high yield potentials as a result of synergistic nutrient interactions.
iii. Help in enabling the plant to resist the damage from pests and diseases and to tolerate relatively dry moisture conditions.
iv. A favorable influence on crop quality and biochemical constituents of the produce (protein, oil, fatty acids, nitrate, etc.).
v. Minimizing the amount of fertilizer nutrients left in the soil after harvest, thus reducing the potential for negative environmental impacts through leaching of nutrients and emission of greenhouse gases.

Research conducted in different countries during the last few decades has reduced uncertainty in the estimates of usefulness and losses from fertilizer N vis-à-vis other inputs in field crops and has evaluated the impact and cost–benefit ratio of their uses and resultant interactions for food production. However, we are still a ways off from a satisfactory comprehension of this phenomenon, especially when looking at the interactive relationships of different inputs together. Therefore, in consideration of the aforementioned discussion, we see the following research needs.

1. Data relating fertilizer nutrient rates and soil test indices to grain yield under intensive water management are needed to maximize fertilizer use efficiency.
2. Delineation of areas and situations where N and other inputs are over- or underused.
3. Attempts should be made to work out the N requirements of various crops more closely and accurately avoiding yield limitations due to other nutrients and water, which may be helpful in deciding the optimum rate of N on one hand and synergy with different nutrients and growth factors on the other. Once the intertwined effects of N interaction with other nutrients are reasonably predictable in a particular region, these should be utilized to obtain the potential maximum economical yield.
4. Crop and location-specific fertilizer recommendations should be made available to farmers. This would help in increasing high quality crop

produce, resulting in high economic benefits, keeping agricultural production sustainable, and decreasing pollution.

5. In soils that contain abundant K, the response to K can be expected for the most K-demanding crops only and a separate strategy will have to be evolved. In India and China, however, where almost 50% of the global N fertilizer is used, a K/N ratio of ~0.12 is far below the K/N ratio removed by the crops (0.15–0.84 in grain and 1.05–3.57 in straw). Thus, in regions where crop residues are not returned to the field and/or have degraded soils, deficiencies in P and K may limit the production and quality of crops in the future.
6. Because the majority of landmass in temperate and humid regions is covered by acidic soils, a thorough understanding of interactions of N with Ca and Mg is essential for developing balanced fertilizer application strategies and avoiding crop losses due to antagonistic effects, e.g., of Ca × Mg, K × Ca, and K × Mg interactions.
7. Considering the enormous variety in physiology and morphology of the different field crops and their cultivars, the impact of different traits is of utmost importance for devising efficient nutrient use strategies. Thus, improving the knowledge on such plant traits that determine the nature (synergistic or antagonistic) and extent of interactions would expand our ability to effectively manage balanced and optimum crop nutrition. Based on differences among cultivars, it should be feasible to select and breed high yielding crop cultivars having an extensive root system with a high capability to respond to synergistic nutrient interactions.
8. The potential for imbalance of P and K fertilization may present problems for food production in the future. As N-driven crop production is hardly sustainable, identification and exploitation of factors and technologies for assuring positive interactions of N with other nutrients and water would hold the key for increasing returns from applied N in terms of crop yield and quality, nutrient use efficiency, and minimizing negative environmental effects. The development of packages of management involving several nutrients together, as the situation demands, can effectively enhance their use efficiency in a socioeconomically acceptable fashion.
9. Improvements in the spatial resolution of nutrient interactions are needed to distinguish ***responsive*** and nonresponsive locations, regions, or countries for multinutrient strategies. This should be followed by the development of decision support systems to find out the "best-fit multinutrient management" that considers site-specific settings of natural and socioeconomic factors.
10. As excessive N results in vigorous vegetative growth, leading to greater water loss via transpiration, there is a need to work out the rates of N according to the availability of soil moisture.

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