Integrated nutrient management for sustainable crop production, improving crop quality and soil health, and minimizing environmental pollution

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Abstract

Laboratory, growth chamber and multiyear field studies were conducted with prominent cropping systems of the subtropical northwestern states of India including rice–wheat, rice–mustard, rice–rapeseed, soybean–wheat, soybean–rapeseed, groundnut–wheat, and groundnut–sunflower by including legumes (moongbean, cowpea, sesbania, pigeon pea) to investigate the role of integrated nutrient management (INM) in harnessing economically-viable sustainable production, enhancing nutritive quality of the produce, improving soil health, and minimizing environmental pollution. Besides growing legumes and short-duration pulse crops in crop rotations, the effects of integrated use of organics (farmyard manure, piggery manure, poultry manure, green manures and crop residues) with chemical fertilizers, and impacts of long-term use of INM on enhancing crop productivity were studied. The results clearly demonstrated that INM enhances the yield potential of crops over and above achievable yield with recommended fertilizers, and results in better synchrony of crop N needs due to (a) slower mineralization of organics, (b) reduced N losses via denitrification and nitrate leaching, (c) enhanced nutrient use efficiency and recovery by crops, and (d) improvements in soil health and productivity, and hence could sustain high crop yields in various cropping systems ensuring long-term sustainability of the system.

Key Words

Food security, nutrient transformations, nitrate and P leaching, greenhouse gases, climate change.

Introduction

One of the most important challenges facing humanity today is to conserve/sustain natural resources, including soil and water, for increasing food production while protecting the environment. As the world population grows, stress on natural resources increases, making it difficult to maintain food security. Long-term food security requires a balance between increasing crop production, maintaining soil health and environmental sustainability. In India, effective nutrient management has played a major role in accomplishing the enormous increase in foodgrain production from 52 million tons in 1951-52 to 230 million tons during 2007-08. However, application of imbalanced and/or excessive nutrients led to declining nutrient-use efficiency making fertilizer consumption uneconomical and producing adverse effects on atmosphere (Aulakh and Adhya 2005) and groundwater quality (Aulakh *et al.* 2009) causing health hazards and climate change. On other hand, nutrient mining has occurred in many soils due to lack of affordable fertilizer sources and where fewer or no organic residues are returned to the soils.

Arid and semiarid subtropical soils of northwestern states of India, developed under harsh climate, are inherently poor in organic matter, fertility and water-holding capacity. In these soils, N, P and S deficiencies are principal yield-limiting factors for crop production. INM, which entails the maintenance/adjustment of soil fertility to an optimum level for crop productivity to obtain the maximum benefit from all possible sources of plant nutrients – organics as well as inorganics – in an integrated manner (Aulakh and Grant 2008), is an essential step to address the twin concerns of nutrient excess and nutrient depletion. INM is also important for marginal farmers who cannot afford to supply crop nutrients through costly chemical fertilizers. This paper summarizes the results of extensive research work carried out with dominant crop rotations of major field crops grown in the subtropical northwestern states of India to investigate the role of INM in harnessing economically-viable sustainable production of prominent cropping systems, enhancing nutritive quality of the produce, improving soil health, and minimizing environmental pollution.

Methods

The subtropical regions of northwestern states of India have summer and winter crop-growing seasons where summer is characterized by high temperature and rainfall (i.e. monsoons); the winter is often dry with low temperature, which is suitable for growing field crops under irrigated conditions. The application of organic manures and raising leguminous crops for green manure (GM) are generally followed in summer crops, as the temperature and moisture conditions are favourable. Several laboratory, growth chamber and field studies were conducted to study the effects of growing legumes and short-duration pulse crops in crop rotations, integrated use of organics – farmyard manure (FYM), piggery manure, poultry manure, GM and crop residue (CR) with chemical fertilizers, and impacts of long-term use of INM on enhancing crop productivity. Dominant crop rotations of major field crops such as rice–wheat, rice–mustard, rice–rapeseed, soybean–wheat, soybean–rapeseed, groundnut–wheat, and groundnut–sunflower were studied. Leguminous crops (sesbania, cowpea, mungbean), which accumulate biomass at a rapid rate, were grown when fields were vacant and incorporated into soil at or near flowering as GM. Crop yields and nutrients uptake, transformations and leaching of nutrients in soil, gaseous N losses and denitrification, leaching of nutrients, biological N fixation (BNF) by legumes estimated using ^{15}N dilution technique, soil quality parameters such as available nutrients, SOC, water soluble C, particulate organic matter C, light fraction organic matter C, microbial biomass C, and conserved soil moisture were measured.

Results

Nutrient transformations and availability under controlled and field conditions

Studies conducted under controlled conditions in growth chamber and laboratory revealed that (a) mineralization of nutrients from added organics was differentially affected by temperature, soil aeration status, crop residue quality, and soil P status, (b) the nutrient release pattern and mineralization were directly related to N, P and S content of organics and inversely to carbon to nutrient ratios; thereby implying that a crop residue with high nutrient concentration and lower C:Nutrient ratio decomposes easily and releases nutrient at fast rate, (c) high N, P or S concentration in crop residue reduces the competition for soil mineral nutrient by microorganisms and thus enhances the decomposition by supporting higher microbial activity, (d) provided evidence that the C:N, C:P and C:S ratios are reliable and simple to determine for describing crop residue quality, (e) organics enhanced denitrification losses from soils under nearly-saturated and flooded conditions, and (f) CO_2 emission from soils, an indicator of C supply to microorganisms, was directly related to denitrification activity. Verification of these findings under field conditions confirmed that (a) sesbania GM that had high N content and narrow C:N ratio mineralized rapidly, which explained the enhanced efficiency of GM, compared to fertilizer N (FN), in supplying N to growing plants and increasing crop yields, N uptake, and N recovery; (b) wide C:N ratio crop residues of wheat, rice and rapeseed caused immobilization of mineral N but with conjoint incorporation of sesbania GM counteracted this deleterious effect, supplied N to rice and increased yields; and (c) incorporation of narrow C:N ratio groundnut residues in conjunction with fertilizer N and P in sunflower crop exhibited fast N and P mineralization even during cool winter; 31 % of groundnut residue-N and 32 % of groundnut residue-P were utilized by the crops, and Olsen-P status of soil increased from initial 12 kg P /ha to 24–43 kg P /ha in INM plots after 4 years of groundnut-sunflower rotation.

However, few revelations noted under controlled conditions, where moisture and temperature regimes were kept constant and plants were not grown, were not observed under field conditions. (a) While organics such as GM, FYM and CR increased N_2O emissions under laboratory conditions, INM did not affect N_2O emissions in rice-wheat rotation under field conditions (Table 1). (b) Application of organics in conjunction with FN enhanced denitrification losses from soils under nearly-saturated and flooded conditions under controlled conditions, whereas INM significantly reduced gaseous N losses as compared to the application of FN alone in rice-wheat system (Table 1). (c) No doubt the increased CO_2 production with INM in soils under rice coincided with enhanced rates of denitrification but the total flux of CO_2-C from rice-wheat system even with the use of organics was far less than CO_2-C consumed by crops for photosynthesis suggesting that high yielding cropping systems are rather sinks than sources of atmospheric CO_2-C. This research work further illustrated that (a) INM significantly improves physical, chemical and biological properties of soil; (b) depending upon the ease of mineralization as related to C:N ratio of added organics, 6 % of added C through sesbania GM, 10 % of groundnut residues, 17 % of rice residue and 21 % of wheat residue was sequestered into the soil in a period of 4 years (Table 1); (c) SOC and other labile pools of C and N were significantly improved with INM plots after 4 years of study (Table 2); (d) while FN had no residual effects, residual GM produced significantly greater yields of a succeeding crop due to the supply of N equivalent to 17-90 kg FN /ha in different crop rotations; for example, GM could save up to 60 kg N /ha in rice and 30 kg N /ha in succeeding wheat or 17 kg N /ha in rapeseed; (e) surface retained crop residues in no-till field conserved soil moisture and enhanced the intrinsic biological N-fixing capacity of soybean by 20 % (Figure 1), thus enabling legumes to meet the large proportion of their N requirement; and (f) INM enhanced crop quality by enhancing the acquisition of nutrients, synthesis of protein, oil and fatty acids.

Table 1. Effect of INM on rice yield, denitrification losses, N_20 emissions and soil organic C.

Treatment	Rice yield (q /ha)	Denitrification losses (kg /ha)	N_20 emissions (kg /ha)	Soil organic C (%)
Control	34	18	6.9	0.37
120 kg FN /ha	56	58	12.4	0.37
GM_{20} + 32 kg FN /ha	59	50	11.8	0.41
CR_6 + GM_{20} + 32 kg FN /ha	59	52	11.8	0.49
LSD (0.05)	2	6	3.4	0.04

FN = 88 kg N /ha through 20 t /ha sesbania green manure; CR = 6 t /ha crop residues

Table 2. Effect of INM on soil organic C, potentially mineralizable N (PMN) and microbial biomass N (MBN) in soybean-wheat rotation under conventional till (CT) and no-till (NT) systems.

Treatments	TOC (Mg C /ha)		PMN (mg N /kg)		MBN (mg N /kg)	
	CT	NT	CT	NT	CT	NT
Control	2.9	3.5	2.7	3.6	5.9	6.4
N_{20} + P_{60}	3.2	3.6	2.9	3.9	9.5	10.4
N_{20} + P_{60}+ 10 t FYM /ha	3.4	3.8	5.1	6.5	16.0	16.8
N_{25}+ P_{75}	3.3	3.6	3.9	5.1	12.7	15.6
Control + CR	3.0	3.7	3.3	4.2	7.0	7.2
N_{20} + P_{60} + CR	3.4	3.8	6.9	8.9	12.9	15.4
N_{20} + P_{60}+ 10 t FYM /ha +CR	4.4	4.8	9.7	12.1	24.3	27.3
N_{25}+ P_{75} + CR	3.7	3.8	8.4	10.3	17.6	20.5

These studies clearly demonstrated that excessive application of N reduces crop yields and results in leaching of NO_3^- to deeper soil layers. Enhanced nitrate accumulation (70 to 74 %) in the 90 to 150 cm depth indicated the possibility of nitrate leaching below 150 cm and into groundwater. While leaching of nitrate beyond plant rooting zone could be substantial in rice fields fertilized with FN in porous soils, INM could minimize potential nitrate leaching as organics act as slow release fertilizers synchronizing N supply with plant need. It is further established that long-term applications of fertilizer P could cause enormous movement of P to deeper layers in a coarse-textured soil having low adsorption and retention capacity for nutrients whereas INM reduces accumulation of labile P in soils as well as downward movement to deeper soil layers.

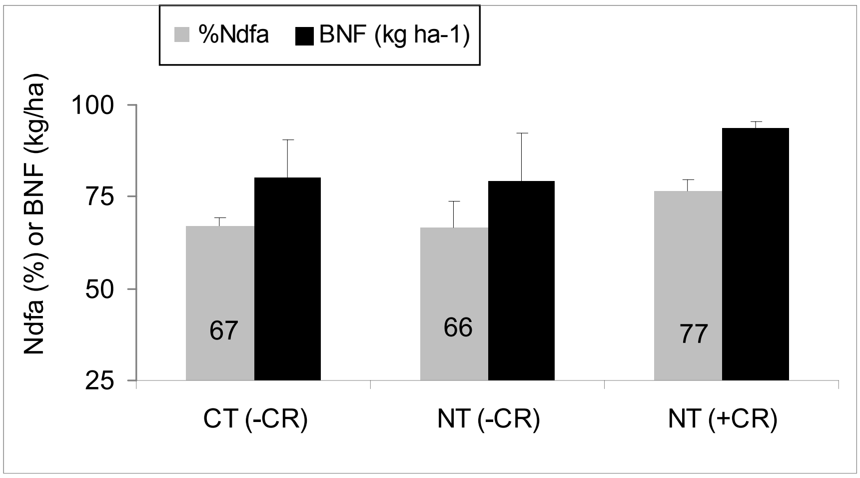

Figure 1. Per cent N derived from atmosphere (% Ndfa) and biological N fixation (BNF) by soybean under conventional-till (CT) and no-till (NT) with or without wheat crop residue (CR).

Practical implications and benefits of INM

The findings on microbial transformations of organic amendments to plant available N, P and S, and gaseous N forms led to the better understanding of N cycling processes to develop most efficient use of organics for the (a) evaluation of agricultural management effects on soil health and productivity, (b) determining the potential of denitrification and emission of greenhouse gases, and (c) aiding in the selection of nutrient management practices for sustainable agriculture. These findings have several practical implications: (a) Incorporation of narrow C:N ratio organics (poultry and green manures) at sowing of crops could release sufficient mineral N to synchronize N supply with crop needs during early growth period, whereas some initial starter N would be needed when wide C:N ratio organics (cattle manure, pressmud, cereal crop residue) are incorporated. (b) In case of substantially enhanced immobilization of mineral N with the

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incorporation of wide C:N ratio crop residues, application of FN would facilitate re-mineralization after about 3-week period. (c) INM has its residual effects producing 9-35 % greater yields of succeeding crops in different cropping systems. (d) Conjoint use of legume GM and FN could alleviate the deleterious effects due to the incorporation of wide C:N ratio cereal crop residues. (f) Incorporation of groundnut crop residues in conjunction with the adequate rates of FN and FP has complementary effects in maximizing the yields, uptake of N and P, and nutrient use-efficiency in groundnut-sunflower rotation. INM enhances the yield potential of crops over and above achievable with recommended fertilizers. For example seed yield of mustard increased significantly up to 100 kg FN /ha + 30 kg P_2O_5 /ha (which are recommended rates) but decreased thereafter with further increase in FN rate to 150 kg FN /ha due to excessive vegetative growth and resultant lodging. In contrast, all through 4 years, the combined application of GM with 100 kg N /ha further improved the yield potential of mustard by 11 %. Similar increase in the yield potential of rice (10 %) and rapeseed (16 %) in other studies illustrated the benefit that any amount of fertilizers cannot achieve.

Development of INM technologies, formulation of strategies and their adoption
These research findings led to the development of several sound INM technologies: (a) Green manuring in rice–wheat, rice–mustard, and rice–rapeseed is cost effective and economically viable. (b) Under constrained water resources, GM produced during the mild-rainy season and applied to rapeseed is more beneficial than rice-applied GM. (c) Supply of nutrients through the integrated use of 20 t GM and 60 kg FN /ha provides advantages over the use of 120 kg FN /ha alone, producing greater yields of rice and wheat while reducing the use of FN by >50 % in rice and 25 % in wheat. It significantly reduces denitrification losses and diminishes the accumulation of residual NO_3^- in the soil profile, and hence reduces the chances of NO_3^- leaching to groundwater providing environmental benefits. (d) INM through GM, crop residues and FN in a rice-based cropping systems, groundnut-sunflower, soybean-based cropping systems has the long-term benefit of C sequestration and improved soil health resulting in high crop yields, help maintain balanced nutrients supply, check multinutrient deficiencies and sustain crop yields at a higher level.

Conclusions
These studies provided an insight into the practical understanding, and illustrated beyond any doubt, how INM strategy can result in agronomically feasible, economically viable and environmentally sound sustainable crop production systems by enhancing soil fertility and C sequestration, and reducing N losses and emission of greenhouse gases. Formulation and adoption of careful strategies to propagate the long-term usefulness of INM in providing nutrients and improving the soil health, educative extension efforts about the economic and environmental benefits of INM, regulations for prohibiting the burning of crop residues, and some incentives for encouraging the crop residue incorporation as a means of disposal could lead to the adoption of such eco-friendly practices.

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