Significance of Biological Nitrogen Fixation and Organic Manures in Soil Fertility Management[1]

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Abstract

A review of the literature on the role of leguminous crops and organic manures in soil fertility management confirmed that they can enhance soil productivity. The leguminous crops, either intercropped or in rotation, benefited the associated or succeeding crops. N_2 fixation by leguminous crops is one of the most beneficial effects; the amount of N_2 fixed by a few legume species has been estimated by various measurement methods.

The effect of legume crops is discussed primarily from the viewpoint of the transfer of N to associated and succeeding crops. Evidence obtained by using ^{15}N-labeled legumes suggests that the amount of N transferred from the legume crop to an associated crop is not substantial and that a major part of N in legume residue is not made available to the succeeding crop. The beneficial effect of legume could not be ascribed solely to N mineralization, and the acidifying effect of legume roots may be an additional benefit.

The extent of crop response to organic manure, i.e., farmyard manure (FYM), undecomposed crop residue, and green manure, varies with locations, time and method of application, and environmental conditions. Organic manure influences soil productivity through its effect on physical, chemical, and biological soil properties. Several long-term experiments in India have shown that organic manure improved the soil physical properties by reducing bulk density, increasing water-stable aggregates, and increasing field capacity. Continued application of organic manure increased organic carbon and nitrogen content and cation exchange capacity, as well as the population of bacteria, fungi, and actinomycetes. Increased N_2 fixation by associative N_2-fixing bacteria was noticeable.

Introduction

Biological N_2 fixation and organic manures occupy an important place in the soil N cycle. Under arable upland conditions, legumes are a major source of N_2 fixation; the source of organic manure is plant residue and FYM. The growing of crops that fix N_2 and the application of organic manures maintain soil fertility by minimizing the loss of N and other nutrients from the soil.

The beneficial effect of a legume crop on soil fertility or on other nonleguminous crops in association or in rotation with the legume has been a subject of interest among research workers. It is generally accepted that N_2 fixation by legumes reduces the rates of soil N depletion and that a major part of N_2 fixed by a legume crop becomes available directly or indirectly to the associated or succeeding crops. However, there is much variation in assessing the extent of these benefits and much controversy concerning the mechanism of N transfer from the legume to associated or succeeding crops.

Organic manures are generally applied to the land in order to recycle nutrients, improve soil structure, and accumulate organic matter in the soil. It has been recognized that efficient and effective use of organic manures provides benefits to crop productivity by immobilizing nutrients that are otherwise susceptible to leaching and by enhancing the activity of soil microorganisms and fauna.

The use of legumes and organic manures as a means of returning nutrients to the soil and enhancing soil productivity has declined in the countries with intensive agriculture and in the areas where chemical fertilizers are abundantly applied. However, in the humid tropics and

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the semiarid tropics (SAT) where the use of chemical fertilizer is limited, biological N_2 fixation by legumes, grown in rotation or intercropped with cereals, and addition of organic manures are very important factors in achieving good crop yields and in maintaining adequate nutrient levels in the soil.

The emphasis in this review is on the improvement of the nutrient status of the soil; therefore, the review will focus mainly on the quantity of N_2 fixed and the fate of that N_2 fixed by legumes and in legume residue, as well as the effects of organic manures on improving productivity of the soil and the soil properties.

Biological Nitrogen Fixation

Benefits of Legumes

The fact that legumes are a common component of crop rotation, intercropping, or mixed cropping has led to the thought that N_2 fixed by legumes contributes to maintaining soil fertility, particularly soil N, and that it may be directly or indirectly used by associated or succeeding crops. There are several reports and reviews on the advantages of including legumes in a cropping system over sole cropping of nonlegumes; however, only some of the recent results obtained in India are discussed here.

Legume-wheat and fallow-wheat sequences have been compared with a sorghum-wheat sequence for 3 years (Shinde et al., 1984). Generally, the former two sequences performed better than did the latter one at a medium level of N fertility management, but at a higher level of fertility management, the advantages of legumes on succeeding wheat were not clearly evident. Pearl millet (*Pennisetum glaucum*) yielded more when sown after fallow, cowpea (*Vigna unguiculata*), or greengram (*Vigna radiata*) than after maize (*Zea mays* [L.]) (Narwal and Malik, 1987). After 4 years of continuous crop rotation, the total N increased in soil under all rotations in which legume was included but not in a maize-wheat-fallow system, with the maximum buildup of N observed in rotations with groundnut (*Arachis hypogaea* [L.]) (Thind et al., 1979). Rainy-season grain legumes showed appreciable residual and cumulative effects on N concentration in an unfertilized wheat crop when phosphorus was applied (Dhama and Sinha, 1985). Winter grain legumes increased the N and P status of the soil compared with cereal or fallow and increased the yield and N uptake of maize following legumes (Ahlawat et al., 1981).

Yield was significantly increased when wheat was grown following sorghum intercropped with cowpea or groundnut compared with following sole sorghum in the previous season (Waghmare and Singh, 1984). Grain yield was significantly increased for maize intercropped with blackgram (*Vigna mungo* [L.]), cowpea, and mungbean (*Phaseolus aureus*) as compared with sole maize and maize intercropped with groundnut (Das and Mathur, 1980). Intercropping of maize with blackgram, greengram, groundnut, or cowpea was found to increase the soil N content more than did maize alone; in general, in soils with lower levels of N, inclusion of legumes resulted in increased soil N content (Gangwar and Kalra, 1980). The All India Coordinated Millet Improvement Project compiled the results of intercropping pearl millet with pulses and oilseeds from 1974-80, and the consolidated data showed that the pearl millet-greengram system was consistently more productive than pure pearl millet (Borse et al., 1983).

Estimation of Nitrogen Fixation

A leguminous crop acquires N through absorption of soil N and through fixation of atmospheric N_2. The ratio of N acquired through each of the two processes to total N in the plant varies with plant species and environmental conditions. Accurate measurement of the amount of N_2 fixed under various environmental conditions is a prerequisite for assessing the role of leguminous crops in crop and soil management.

The following techniques are commonly used for estimating N_2 fixation in the greenhouse and the field:

1. Acetylene (C_2H_2) reduction.
2. ^{15}N gas incorporation.
3. ^{15}N isotope dilution.
4. Natural abundance of ^{15}N.
5. N difference method.
6. N balance.

Acetylene Reduction—The acetylene reduction assay makes use of the fact that the enzyme responsible for N_2 fixation, nitrogenase, can reduce acetylene (C_2H_2) to ethylene (C_2H_4) as well as N_2 to NH_3 (Hardy et al., 1973). Acetylene and ethylene can be easily and rapidly analyzed by a gas chromatograph. The technique requires incubation of plants in a closed chamber along with acetylene. Ethylene formed by the enzyme is estimated by using gas chromatography. Because a closed chamber is used, this technique is not suitable for long-term measurement of N_2 fixation. A major problem with this technique is calculation of the ratio of ethylene formed to nitrogen to be reduced. The theoretical conversion ratio of C_2H_2 reduction to N_2 fixed, calculated from electron ratio, is 3 to 1, but this theoretical ratio is not universally applicable to all N_2-fixation studies (Bergerson, 1980).

^{15}N Gas Incorporation–Nitrogen gas that is labeled with the stable isotope ^{15}N is placed in the atmosphere of a closed chamber in which the test plants are growing. The amount of N_2 fixed is calculated by the amount of ^{15}N incorporated into the plant (Burris and Miller, 1941). Nitrogen gas is a genuine substrate of nitrogenase, and hence the value obtained by this method is a realistic estimate of N_2 fixation. However, the use of this method is restricted to only short-term measurements because of the requirement for a closed chamber and the high cost of ^{15}N-labeled gas.

^{15}N Dilution–The principle of this method is that an N_2-fixing plant growing in a medium enriched by ^{15}N fertilizer contains less ^{15}N in the plant than does a nonfixing plant growing in the same medium (McAuliffe et al., 1958). This is because the nonfixing plant obtains all its N from the ^{15}N-enriched medium, whereas the fixing plant obtains a significant portion of its N from the atmosphere, which is 99.637% ^{14}N; the result is an overall lower ^{15}N enrichment in the plant tissue (McAuliffe et al., 1958). Major difficulties in applying this technique under field conditions include selecting an appropriate nonfixing control, providing uniform distribution of the ^{15}N label at the soil depths where fixing and nonfixing plant roots are growing, and ensuring that the level of ^{15}N-enriched fertilizer is not so high that it inhibits N_2 fixation. The main advantage of this technique is that it can be used with ease for the measurement of N_2 fixation in the field without disturbing the soil-plant system during the experiment.

Natural Abundance of ^{15}N–This method of calculating percent N derived from atmospheric N_2 is based on the same concept as that for the use of ^{15}N dilution and makes use of the differences between the abundance of ^{15}N in the soil and that of the atmosphere. Usually, the natural abundance of ^{15}N in the soil is slightly higher than that in the atmosphere, possibly as a result of isotopic discrimination during long-term N cycling between the soil and the atmosphere. Although ^{14}N is identical to ^{15}N in terms of chemical properties, there is a difference in their masses. In other words, with this method, the amount of naturally occurring ^{15}N in the soil that is in excess of that in the atmosphere is considered to be an ^{15}N tracer. Because the difference in ^{15}N between the soil and the atmosphere is usually very low, the measurement of N_2 fixation using this technique requires mass spectrometers with high precision, and even a slight change in ^{15}N value results in significant changes in N_2-fixation estimates. Nevertheless, a major advantage of this method is that the measurements can be made without addition of ^{15}N-labeled compounds and without disturbing the plant-soil system in the field. Thus fixing and nonfixing plants have equal access to profile variation in ^{15}N with depth.

N Difference Method–This method, which simply compares N yields of fixing and nonfixing plants, is often used in the fields to obtain rough estimates of N_2 fixed by legumes. The method requires an appropriate non-N_2-fixing control plant which must possess the same efficiency of use of soil or fertilizer N as the N_2-fixing plant to which it will be compared. This classical method has generally been used by agronomists in fields where the N_2-fixing plant and nonfixing plant are simultaneously grown.

N Balance Method–If all the inputs of N to a given field through precipitation, fertilizer, etc. (except N_2 fixation) are measured and all removal of N from that field is also measured (leaching, denitrification, and crop harvesting), the positive difference between input and output will be ascribed to N_2 fixation. Such N input and output measurements are possible only in a pot or in the field specially designed for this purpose, and much greater efforts are required to measure the changes in soil N because of a large N pool in the soil and large spatial variability in soil N content. This method will provide a more accurate estimate of N_2 fixation in the field where the experiment is conducted for several seasons or years.

Some Examples of N_2-Fixation Estimates–Some estimates of the amount of N_2 fixed by crops are shown in Table 1. The amount of N_2 fixed by a leguminous species varies not only with genotype, location, and soil fertility but also with the measurement techniques that are employed. In Table 1, the estimates were obtained by N difference, ^{15}N dilution, and natural ^{15}N abundance techniques that do not require the closed chamber and do not disturb the plant-soil system.

Because these techniques use a nonfixing plant as a reference, their estimates are generally fairly close if the measurement is done by comparing N_2-fixing and nonfixing varieties of the same plant species at the same location. However, the use of a nonfixing variety limits the precision of these techniques because they are based on the incorrect assumption that the roots of both plant varieties exploit the same soil volume. However, the greatest advantage of these methods is that they provide an integrated estimate over time under field conditions.

Role of Nitrogen Fixation

It is universally accepted that the beneficial effect of legumes is through addition of N_2 fixed in root nodules to the plant-soil system in sole cropping, in intercropping, or in rotation. In almost all the trials where benefits were obtained from growing legumes, the role of legume has been examined from the viewpoint of nitrogen economy. Traditionally, it has been said that the major effects of legume are through maintenance of adequate soil N and

Table 1. Some Examples of Estimates of N_2-Fixation by Grain Legumes

Crop	Estimation Method	N_2 Fixed (kg N ha^{-1})	Percent N Derived From N_2 Fixation (%)	Reference
Soybean	N difference	130	51	Bhangoo and Albritton (1978)
	^{15}N dilution	108	60	Deibert et al. (1980)
	Natural ^{15}N	49	48	Yoneyama et al. (personal communication)
Groundnut	N difference	113[a]	85	Yoneyama et al. (personal communication)
	^{15}N dilution	152	92	Giller et al. (1987)
	Natural ^{15}N	112[a]	85	Yoneyama et al. (personal communication)
Pigeon pea	N difference	69	52	Kumar Rao and Dart (1987)
	^{15}N dilution	69	88	Kumar Rao et al. (1987)
Chick-pea	N difference	26[a]	44	Giller et al. (1988)
	^{15}N dilution	36[a]	61	Giller et al. (1988)
Cowpea	N difference	53[a]	NA	Eaglesham et al. (1982)
	^{15}N dilution	77[a]	NA	Eaglesham et al. (1982)

a. Measurement was done on the same genotype at the same location and time.

NA = not available.

contribution of available N to an associated crop or the succeeding crop. However, it has sometimes been difficult to attribute the beneficial effects solely to increased availability of N to other crops (Ketcheson, 1980).

Transfer of Fixed N_2–Two important effects of fixed N_2 are its transfer to the associated crop and its transfer to the succeeding crop.

Evidence for the transfer of symbiotically fixed N_2 to an associated crop has not been directly obtained by feeding isotopically labeled N_2 gas to the legume. There have been reports (Van Kessel et al., 1985; Francis and Read, 1984) of direct hyphal linkage of mycorrhiza allowing transportation of nutrients between two root systems. It is possible that nitrogen fixed by a legume in intercropping is transferred through such a hyphal linkage to an associated nonlegume, but the nature and the quantity of this transfer system have not been substantiated under field conditions.

In a 3-year N balance study, Simpson (1976) estimated that 20% of total nitrogen in subterranean clover (*Trifolium subterraneum*), 6% of that in white clover (*Trifolium repens*), and 3% of that in lucerne (*Medicago sativa*) were transferred to the associated grass, cockfoot (*Dactylis glomerata*). However, in his experiment sole crops or intercrops were grown in the same plots, and hence the amount of N transferred to the grass may have consisted of concurrently fixed N or the N_2 fixed previously.

It is important to use an ^{15}N-labeled source in measuring the transfer of N, but data obtained using ^{15}N in India are not available. An estimate of the transfer of N by the ^{15}N dilution technique in intercrops or mixed cropping is based on the calculation of the enrichment of ^{15}N in the legume and the associated crop. The ^{15}N enrichment of Kleingrass (*Panicum coloratum*) grown with siratro (*Macroptylium atropurpurem*) was lower than that for Kleingrass grown in pure stand by 13% and 6%, which accounted for 14% and 5% of the total N in the Kleingrass for the low and high rates of N fertilization, respectively (Ismaili and Weaver, 1987). The maize intercropped with cowpea showed a significant (52%) dilution of ^{15}N in comparison with the sole-cropped maize (Eaglesham et al., 1981), and it was concluded that N excreted by the intercropped legume gave significant benefit to the associated maize.

Ledgard et al. (1985) used a new method in which subterranean clover was labeled with ^{15}N by foliar absorption, and the transfer of N from the subterranean clover to the associated ryegrass (*Lolium rigidum*) was measured. Over a 29-day period, 2.2% of the N from the subterranean clover was transferred to the ryegrass.

The above evidence obtained by using ^{15}N compounds, though not as direct as the estimate by the ^{15}N gas incorporation method, suggests that N from the legume is transferred to the associated nonlegume during the same growing season. However, the amount of N transferred does not seem to have been substantial except in the study reported by Eaglesham et al. (1981). The main pathway of N transfer may be as sloughed-off roots, N excreted from legume roots, and decomposition of nodules.

A second beneficial effect of fixed N_2 is its transfer to a succeeding crop. Cowpea and groundnut sole crops have been shown to benefit the succeeding maize crop in terms of increased grain and dry-matter yields equivalent to 60 kg N ha^{-1} supplied through fertilizer (Dakora et al., 1987). At a medium level of fertility management, rainy-season greengram or cowpea provided 30 kg N ha^{-1} for succeeding post-rainy maize (Shinde et al., 1984). The N requirement of maize following a sole crop pigeon pea was reduced by 38-49 kg N ha^{-1} compared with maize following either fallow, sole sorghum, or sorghum/pigeon pea (*Cajanus cajan*) intercrop (Kumar Rao et al., 1983). Similarly, a preceding crop of pigeon pea reduced the N requirement of a succeeding wheat crop by 30 kg N ha^{-1} (Narwal et al., 1983).

Beneficial effects of residual N on subsequent crops have been demonstrated not only for sole legume crops but also for intercropped legumes. Intercrops of sorghum with cowpea, groundnut, or greengram saved 18 to 55 kg N ha^{-1} for the target yield of 4.0 tonnes of the wheat that followed (Waghmare and Singh, 1984).

The magnitude of the residual N effect on a succeeding crop depends on the preceding cropping system, preceding legume species, and succeeding crop species and on the method of estimation. In most cases in the SAT, the contribution by legumes of residual N to the succeeding crop has been estimated to be 30 to 70 kg N ha^{-1}. However, these values have been obtained through N fertilizer equivalence methods and do not indicate the exact amounts of N derived from the preceding legumes.

The amount of N transfer from the preceding legume depends not only on the rate of decomposition of legume residue but also on the amount of legume N that is released and made available to a succeeding crop. Therefore, it is essential to know the source of N in the succeeding crop. For that purpose, the use of an ^{15}N-labeled legume material will be a good guide in that the legume N can be distinguished from the soil N during decomposition. As far as we know, no experiment with ^{15}N-labeled legumes has been conducted in India.

Vallis (1983) applied dried ^{15}N-labeled siratro to Rhodes grass (*Chloris gayana*) pasture in Queensland, Australia, and examined the recovery of the ^{15}N. The cumulative recovery of ^{15}N in Rhodes grass shoots after the first, second, and third years was 13.7%, 16.8%, and 14.5%, respectively, of the initial amount added.

In southern Australia, Ladd et al. (1981) incorporated unground ^{15}N-labeled *Medicago littoralis* material into the fields and allowed it to decompose for 8 months before sowing wheat. The wheat took up only 11%-17% of legume residual N, the amount of which corresponds to 5%-10% of total N in the wheat. In a subsequent study (Ladd et al., 1983), ground ^{15}N-labeled *Medicago littoralis* was used and allowed to decompose for 7 months in successive years. The first wheat crop took up only 28% of the legume N, corresponding to 6.1% of the total N in the wheat, and the second crop took up less than 5% of the N in the legume incorporated in the first year.

Thus, a major part of the N in a legume residue is not made available even to the succeeding crop. The rate of N released from legume residue is controlled by the rate of decomposition, which varies with chemical composition of the plant or root, environmental conditions, type of soil, soil organisms, and management practices.

All the available information on decomposition of ^{15}N-labeled legume residues indicates that much lower mineralization of N occurs than is estimated by biomass yield and N yield methods. The discrepancy in the estimates may be ascribed to a significant "priming" effect of legume residue incorporation on soil organic N mineralization and to the fact that a large part of the beneficial effect of legume residue on the succeeding crop is not directly related to N mineralization.

Rhizosphere pH Changes Induced by N_2 Fixation–It is known that nitrate-fed plants make the rhizosphere more alkaline, whereas plants using ammonium-N sources make the rhizosphere acidic due to establishment of an electrochemical equilibrium. When legumes fix atmospheric N_2, the cation absorption usually exceeds the anion absorption and, consequently, the rhizosphere becomes comparable with that of ammonium-fed plants. It has been calculated that a well-nodulated legume root induces a reduction in the average soil pH of about 0.14 units in

100 days (Nye and Kirk, 1987). Therefore, some nutrients will become more available in the rhizosphere of N_2-fixing legumes than in that of nitrate-fed plants.

The availability of phosphorus, for example, is enhanced in soil of lower pH. Soybean (*Glycine max*) fertilized with ammonium-N (and therefore comparable with N_2-fixing soybean) decreased the pH of the rhizosphere and stimulated P uptake (Riley and Barber, 1971). Increased capacity for solubilizing P by N_2-fixing legumes has been demonstrated by using sparingly soluble phosphate rock. The N_2-fixing alfalfa (*Medicago sativa*) plants used phosphate rock more efficiently than did the nitrate-fed plants (Aguilar and van Diest, 1981). The tropical legume *Pueraria javanica* mobilized even very insoluble phosphate rock because of the acidifying effect in its rhizosphere, and the quantity of acid produced by *Pueraria* was calculated to be 10 kmoles H+ ha^{-1}, which would require 500 kg ha^{-1} of calcitic limestone in order to neutralize the rhizosphere.

Under upland conditions, nonleguminous crops, whether fertilized with N or nonfertilized, generally acquire N as nitrate. On the other hand, N_2-fixing legumes influence chemical changes in the rhizosphere differently than the plants that are taking up nitrate-N. In the long run, the form in which the legumes acquire N will influence not only the soil in the rhizosphere but also the bulk soil through alteration of the pattern of absorption of other nutrients. Thus, it would be worthwhile to assess the effect of legumes on the rhizosphere pH and accompanying changes in the availability of other nutrients.

Organic Manures

Crop Response to Organic Manures

Organic matter has received considerable attention as a source of nutrients for plant growth. The classical experiments at Rothamsted, United Kingdom, indicated no superiority of FYM over NPK fertilizers in maintaining crop yields (Johnston and Mattingly, 1976). However, with the introduction of high-yielding crop varieties, evidence is accumulating from the long-term tests that FYM and other organic manures can give larger yields than can be obtained with equivalent fertilizer use (Johnston and Mattingly, 1976; Narayanswamy, 1968; Sahu, 1971).

Farmyard Manure or Compost—The response of crops to FYM application depends on several factors such as degree of humification, maturity of the compost, its C:N ratio, the time and method of its application, soil type, agroclimatic conditions, and moisture regime of soil during the growth of the crop.

Tables 2 and 3 summarize the results of several experiments conducted at different locations in India to study crop responses to FYM application. The results of 210 experiments with irrigated wheat and 71 experiments with rainfed wheat showed that FYM application at 12.6 tonnes ha^{-1} increased the yield of irrigated wheat by 80-300 kg ha^{-1} with an average response of 200 kg ha^{-1}. However, under rainfed conditions the response obtained to an application of 6.3 tonnes ha^{-1} FYM was lower (85 kg ha^{-1}) (Table 2). Similarly, data from several experiments with sugarcane, cotton, potato, and other vegetable crops have shown increased yields with FYM application though Dhingra et al. (1979) failed to obtain increased yields of irrigated wheat with application of 10 tonnes ha^{-1} FYM and 60 kg P_2O_5 ha^{-1}.

In trials conducted in India using different crop rotations (Table 3), incorporation of FYM at 10-15 tonnes ha^{-1} every year along with the recommended dose of NPK produced higher crop yields than did the NPK treatment alone. The highest average inerease in yield over 12 years for the crops grown in a rotation was observed in acidic submontane soil at Palampur, followed by the red loam soil at Hyderabad and medium black soil at Jabalpur. At all the locations (except at Barrackpore), FYM application increased the yield of the first crop in the rotation over the non-FYM treatment, and generally positive yield effects were observed in succeeding crops in the rotation, irrespective of soil type (Table 3).

Undecomposed Crop Residues—Crop residues can be used directly for improving the soil productivity. Direct incorporation of crop residues in the soil, along with appropriate management practices, or use as a mulching material on the soil surface has proven to be beneficial in improving soil physical properties and, in some cases, has led to increased crop yields. However, when low-N materials, such as cereal straw, were plowed into soil, it was found that additional fertilizer N was needed to narrow the C:N ratio in order to avoid adverse effects on crop yields by immobilization of soil N (Bear, 1948; Gupta and Idnani, 1970; Gaur and Mathur, 1979; Ganry et al., 1978).

When ^{15}N was used in a lysimeter experiment on a sandy soil, it was found that straw incorporation depressed the grain yield by 32%. This effect was mainly due to immobilization of fertilizer N and was alleviated by application of additional N (Ganry et al., 1978). The average crop yield data for 2 consecutive years showed that sugarcane trash, rice straw + water hyacinth (1:1), and rice

Table 2. Summary of Experiments on Response of Different Crops to FYM/Compost Application in India

Number of Locations	Number of Experiments	Crop	FYM/Compost Applied	Response Range	Response Average
			($t\ ha^{-1}$)	($kg\ ha^{-1}$)	
63	341	Rice	12.6	99-216	168
31	210	Wheat (irrigated)	12.6	82-295	202
14	71	Wheat (unirrigated)	6.3	74-140	85
19	258	Sugarcane (*Saccharum*			
		officinarum)	25.1	3,700-11,700	8,000
10	71	Cotton (irrigated)	12.6	39-81	56
25	294	Cotton (unirrigated)	6.3	12-22	16
1	1	Sorghum	25	-	1,220
1	74	Sorghum (unirrigated)	5	-	1,340
1	48	Sorghum (irrigated)	5	-	1,280
1	74	Finger millet (unirrigated)			
		(*Eleusine coracana*)	5	-	940
2	48	Finger millet (irrigated)	5	-	1,660
		Pearl millet (irrigated)	5	-	610
		Wheat (irrigated)	5	-	320
1	6	Sweet potato (unirrigated)			
		(*Ipomoea batatas*)	11.2	-	2,760
1	3	Sweet potato (irrigated)	11.2	-	1,080
3	13	Potato (irrigated)			
		(*Solanum tuberosum*)	22.4	-	1,490
1	7	Potato (unirrigated)	37	-	3,890
2	3	Potato (irrigated)	37	-	1,070
1	3	Tapioca (irrigated)			
		(*Manihot utilissima*)	11.2	-	455
1	2	Onion (*Allium cepa*)	11.2	-	2,980
1	2	Onion	24.4	-	5,410
1	8	Chilies (dry)	11.2	-	74
		(*Capsicum annum*)			
1	4	Chilies (dry)	12.5	-	620
		(*Capsicum annum*)			
1	2	Okra (*Abelmoschus esculentus*)	11.2	-	235
	2	Okra	12.5	-	360
1	3	Tomato	11.2	-	175
		Tomato	22.4	-	870
1	4	Brinjal (*Solanum melongena*)	12.5	-	660
		Brinjal (*Solanum melongena*)	25.0	-	370
1	1	Fenugreek (*Trigonella*	5.6	-	-120
		foenum-graecum)			
	1	Fenugreek (*Trigonella*	11.2	-	350
		foenum-graecum)			
	1	Fenugreek (*Trigonella*	12.5	-	430
		foenum-graecum)			
	1	Fenugreek (*Trigonella*	25.0	-	590
		foenum-graecum)			

- = Not available.

Source: Derived from Garg et al. (1971); Krishnamoorthy and Ravikumar (1973).

Table 3. Summary of Long-Term Manurial Experiments on Response of Different Crops to FYM Application in India[a]

Location	Number of Crops	Crop	Soil Type	Average Response to FYM Application ($kg\ ha^{-1}$)
Barrackpore	12	Rice	Alluvial	-10
	13	Wheat	Sandy loam	30
	13	Jute		-5
Ludhiana	13	Maize	Alluvial	680
	14	Wheat		120
	14	Cowpea (fodder)		35
New Delhi	3	Maize	Alluvial	330
	11	Wheat	Sandy loam	420
	10	Cowpea (fodder)		-130
Coimbatore	10	Finger millet	Medium black	505
	9	Cowpea	Clay loam	90
	7	Maize		510
Jabalpur	12	Soybean	Medium black	220
	12	Wheat	Clayey	440
	9	Maize (fodder)		890
Bangalore	7	Finger millet	Red loam	100
	4	Maize	Sandy loam	-110
	10	Cowpea		10
Ranchi	12	Soybean	Red loam	270
	10	Wheat	Silty clay loam	120
Hyderabad	13	Rice (rainy season)	Red loam	560
			Sandy clay loam	
	13	Rice (post rainy season)		760
Bhubaneswar	12	Rice (rainy season)	Lateritic	430
	12	Rice (post rainy season)	Sandy	530
Palampur	12	Maize	Submontane	1,430
	13	Wheat	Silt loam	655
Pantnagar	13	Rice	Foot hill (Terai)	690
	13	Wheat	Silty clay loam	450
	8	Cowpea (fodder)		110

a. In all the experiments 10-15 $t\ ha^{-1}$ FYM was applied every year to the first crop of the rotation.

Source: Derived from ICAR (1986).

straw applied at 2.5 and 5 tonnes ha^{-1} increased wheat yields even when the wastes were applied without mineral N addition (Table 4; Bhardwaj, 1985). Incorporation of straw at 18 tonnes ha^{-1}, 15 days prior to sowing, at a depth of 15 cm gave yields similar to those obtained by application of 200 kg N ha^{-1}. However, incorporation of straw at shallow depths (7.5 cm) reduced crop yields. Significantly higher increases in yields were obtained when one-third of the organic material was incorporated as neem cake along with the straw (Gaur and Mathur, 1979). In a sandy soil, incorporation of wheat straw at 18 tonnes ha^{-1} alone or with mineral N addition plus inoculation with straw-decomposing microorganisms resulted in increased yields of groundnut (Table 4) and also increased uptake of N and P by the groundnut crop (Wani and Shinde, 1980).

Crop residues left on the soil surface as a mulch also have some potential for erosion control, soil fertility maintenance, and increased microbial activity in the soil (McCalla et al., 1962; Agboola, 1982). Mulching adds considerable amounts of nutrient to the soil, and some mulches interact with fertilizer to reduce soil pH. Some straw mulches such as *Typha* and paddy straw may cause nutrient imbalance and toxicities because of the high amounts of Mn and Al they may release during decomposition. The beneficial effects of leguminous mulches appear to be due to their lower C:N ratio (Agboola, 1982). However, when crop residues are left on the soil surface, crop yields are occasionally reduced because of phytotoxic substances released from most crop plants though the phytotoxic effect decreases as the decomposition period is extended (Guenzi et al., 1967; Borner, 1960; Patrick and Koch, 1963). It has been observed that wheat straw contained the least toxic substances, causing only a 6% reduction in root growth of wheat seedlings, and that all the phytotoxic material disappeared from wheat and oat residues after 8 weeks of field exposure. At the end of 8 weeks, corn residues were still quite toxic while sorghum residues remained highly toxic and caused 37%-85% reduction in root growth of wheat test plants during a period of 16 weeks (Norstadt et al., 1967).

Green Manures – The practice of green manuring has been used to improve the soil productivity. However, it is now well established that green manures have a negligible effect on soil organic matter levels if continuous cropping is followed. Singh (1963) summarized the conclusions of several studies on the positive effects of green manures in the restoration of soil organic matter in tropical regions. He reported that, even after removal of the aboveground parts of sunn hemp (*Crotolaria juncea*) grown as a green manure crop, yields of the subsequent crop were still increased.

It has been observed that several accessions of *Sesbania* produced dry-matter yields ranging from 8 to 17 tonnes ha^{-1} and added 70-245 kg N ha^{-1} to the soil depending on the age of the plant at the time of incorporation (Singh, 1982; Ghai et al., 1985; CSSRI, 1985). Maximum N content of different *Sesbania* species was observed after 45 days of growth at which time the N content of the plant shoot on a dry-weight basis ranged from 1.06% for *S. peciosa* to 4.84% for *Sesbania sp.* (Ghai et al., 1985). It has therefore been suggested that incorporation of *S. aculeata* be carried out when the crop is 45 days old (Bhardwaj, 1982; CSSRI, 1985). Sunn hemp was found to be superior among the different green manuring crops and added 100 kg N ha^{-1} to soil and increased its available N content (Alikhan et al., 1963; Bansal et al., 1971). During 42 days of growth, soybeans produced 1,880 kg biomass containing 40 kg N ha^{-1}, and much of the N became available within 7-10 days following incorporation. This increased the grain yield of the succeeding maize by an average of 600 kg ha^{-1} over the control which had not received green manure (Pandey and Pendleton, 1986).

Nitrogen-fixing legumes bear nodules on roots. However, three genera, viz., *Sesbania*, *Aeschynomene*, and *Neptunia*, also form stem nodules containing *Rhizobia* and thus are called stem-nodulated legumes. So far, only *S. rostratra* and *S. punctata* have been reported to be stem nodulated (Dommergues et al., 1988), and the shoots have to be inoculated to ensure adequate infection of all the nodulation sites of the plant. Various methods of estimation (isotopic, balance, and difference) have shown that *S. rostratra* fixed 100-300 kg N ha^{-1} in 7 weeks (Rinaudo et al., 1983), indicating that it is one of the most effective N_2-fixing systems known to date (Dommergues et al., 1988). Several field trials carried out in Senegal indicated that, when *S. rostrata* was applied as green manure in rice fields, the succeeding crop yielded 100% more than the control plot, and the subsequent crop yielded 50% more (Rinaudo et al., 1983).

In addition to the contribution to soil N through biological N_2 fixation, a green manuring crop such as *Sesbania* reduces the leaching losses of mineral N because of its deep rooting system. It also mobilizes nutrients such as phosphorus, potassium, and other trace elements from subsoils; these nutrients are likely to be deficient in surface layers (CSSRI, 1985). Despite the advantages attributed to green manuring, it has not gained the acceptance it deserves for several reasons: (1) it gives no immediate income, (2) its effects in tropical soils are short lived, (3) it does not fit into the farmer's traditional mixed-cropping systems, and (4) it requires labor that the

Table 4. Effect of Direct Incorporation of Plant Residues on Crop Yields

Treatment	Crop	Crop Response	Remarks	Reference
Wheat straw at 18 t ha^{-1} incorporated at 15 cm depth + 200 kg N ha^{-1}	Maize	40	Straw yield was increased by 2,000 kg ha^{-1} over 200 kg N ha^{-1} alone treatment	Gaur and Mathur (1979)
Wheat straw at 18 t ha^{-1} incorporated at 7.5 cm depth + 200 kg N ha^{-1}	Maize	-560	Grain yield was reduced due to immobilization of N in top layer. However straw yield increased by 3,000 kg ha^{-1}	Gaur and Mathur (1979)
Wheat straw at 13.5 t ha^{-1} + neem cake at 4.5 t ha^{-1} + 200 kg N ha^{-1}	Maize	1,380	Straw yield was increased by 7,000 kg ha^{-1}	Gaur and Mathur (1979)
Sugarcane trash 5 t ha^{-1} x zero N	Wheat	125	Total N applied through sugarcane trash was 18 kg ha^{-1}	Bhardwaj (1985)
Sugarcane trash 5 t ha^{-1} 120 kg N ha^{-1}	Wheat	380	Total N applied through sugarcane trash was 18 kg ha^{-1}	Bhardwaj (1985)
Rice straw + water hyacinth (1:1) 5 t ha^{-1} x zero N	Wheat	175	Total N applied through rice straw + water hyacinth was 46.5 kg ha^{-1}	Bhardwaj (1985)
Rice straw + water hyacinth (1:1) 5 t ha^{-1} x 120 N	Wheat	690	Total N applied through rice straw + water hyacinth was 46.5 kg ha^{-1}	Bhardwaj (1985)
Rice straw 5 t ha^{-1} x zero N	Wheat	410	Total N added through rice straw was 31 kg ha^{-1}	Bhardwaj (1985)
Rice straw 5 t ha^{-1} x 100 N ha^{-1}	Wheat	310	Total N added through rice straw was 31 kg ha^{-1}	Bhardwaj (1985)
Rice straw 7.5 t ha^{-1}	Rice	760	Nitrogen was applied at 60 kg ha^{-1}	Mandal and Ghosh (1984)
Rice husk 7.5 t ha^{-1}	Rice	930	Nitrogen was applied at 60 kg ha^{-1}	Mandal and Ghosh (1984)
Wheat straw at 18 t ha^{-1}	Groundnut	440	Grain yield of succeeding wheat crop was also increased by 350 kg ha^{-1}	Wani and Shinde (1980)
Wheat straw at 18 t ha^{-1} with C:N ratio adjusted to 36:1 + inoculated with *Penicillium digitatum*	Groundnut	510	Grain yield of succeeding wheat crop was also increased by 400 kg ha^{-1}	Wani and Shinde (1980)
Eupatorium odarum at 20 t ha^{-1}	Wheat Maize	25 370	The soil was acidic clay loam	Bhardwaj (1986)
Maize crop residues incorporated	Maize	270	Average of 5 years experiment	Hegde et al. (1982)
Rice straw at 10 t ha^{-1}	Rice	245	Experiment was conducted on heavy clay soil for four seasons. Straw yield and also N uptake was increased due to application.	Subbaiah et al. (1983)

farmer considers unnecessary. Suggestions for overcoming these problems include growing fodder or grain legumes in a multiple-cropping sequence (Singh, 1975), intercropping shade-tolerant legumes with different food crops, or interplanting legumes with grasses (Agboola, 1982).

Effect of Organic Manures on Soil Properties

Organic manure affects soil productivity through its improved effects on physical, chemical, and biological soil properties though the extent of these effects is generally difficult to assess. It is still more difficult to quantify the effects of individual properties on crop productivity because most of these properties are interrelated with each other and have a cumulative effect on yields.

Physical Properties—A wide range of soil physical properties such as structure, pore space percentage, volume expansion, maximum water-holding capacity, and aeration are directly or indirectly influenced by soil organic matter content.

The effects of organic matter content on soil structure vary for soils of different texture and mineralogical compositions. Favorable effects in terms of reduced bulk density and increased percentage of water-stable aggregates have been observed for FYM applications in India (Table 5). Khaleel et al. (1981) reviewed the results of 42 field experiments dealing with the effects of manures and composts on soil properties. They found highly significant correlations between increased organic carbon content (induced by manure application) and reduced bulk density and between increased organic carbon content and increased field capacity. Increased organic matter content due to continued application of FYM improved the percentage of water-stable aggregates and the permeability of alluvial soils of northern India (Biswas et al., 1964) as well as other soil types (e.g., see ICAR, 1986). Better structural stability was also observed with increases in soil organic matter content due to addition of water hyacinth (Ghani et al., 1967), sugarcane trash (Sandhu and Bhumbla, 1967), compost (Lal and Kang, 1982), and wheat straw (Gaur et al., 1972).

Table 5. Effect of FYM Application on Soil Bulk Density and Soil Aggregate Stability at Different Locations After 7-11 Years of Manuring and Cropping

	Soil Bulk Density			Percent Water-Stable Aggregates >0.25 mm		
Location	Control	NPK	NPK + FYM	Control	NPK	NPK + FYM
	($g\ cm^{-3}$)			(%)		
Barrackpore	1.46	1.44	1.40	19.8	24.1	40.4
New Delhi	1.47	1.45	1.42	14.3	18.7	28.4
Coimbatore	1.40	1.36	1.31	61.3	67.9	65.2
Jabalpur	1.22	1.21	1.18	84.6	86.0	90.1
Hyderabad	1.53	1.68	1.34	70.0	73.0	84.6
Bhubaneswar	1.65	1.63	1.56	NA	NA	NA

Source: Nambiar and Ghosh (1984).

After 44 years of experimentation in the long-term, old permanent manurial experiment (OPM) at Coimbatore, there was no appreciable difference in the physical properties due to cattle manure application at 12.5 tonnes ha^{-1} $year^{-1}$ (Krishnamoorthy and Ravikumar, 1973). However, in a new permanent manurial experiment (NPM) started in 1925 at Coimbatore, which received 2.3 tonnes cattle manure ha^{-1} $year^{-1}$ as basal dressing, favorable increases in pore space percentage, volume expansion, and water-holding capacity were observed after growing 77 crops that received cattle manure and NPK treatments. The increased yields in cattle manure treatments were associated with the improved soil structure (Krishnamoorthy and Ravikumar, 1973). Similarly, incorporation of organic residues, FYM, or pig manure at 25 tonnes ha^{-1} (Shanmugam and Ravikumar, 1980) and also at 10 tonnes ha^{-1} improved physical properties such as hydraulic conductivity, infiltration rate, stability index, and aggregate stability in red sandy loam soils (Ravikumar et al., 1975). Conversely, negligible improvements in structure have resulted from addition of even large quantities of FYM to sandy soils of Egypt (Abdou and Metwally, 1967) and to clayey Vertisols in central India (Venkoba Rao et al., 1967; Lal and Kang, 1982).

Organic matter improves soil aggregation mainly by stimulating earthworm activity and increasing microbial production of a variety of linear organic polymers, such as humic substances of low polysaccharides and polyuronides which bind the particles together into micro- and macro-aggregates.

Favorable effects of organic matter content on water retention and availability have been reported for many Indian soils (Biswas and Ali, 1967, 1969; Somani and Saxena, 1976; and Murali et al., 1979). Increased organic matter content in soils generally results in improved water use efficiency through increased water retention in the root zone, improved root proliferation, and decreased losses due to water runoff. These factors, in turn, result in improved nutrition and better crop growth with the same inputs. In lysimeter studies, green manuring in sandy soils decreased leaching of several major nutrients, particularly N (Jurgens-Gschwind and Jung, 1979).

Chemical Properties – Soil organic matter and added organic materials not only act as a source of nutrients but also influence availability of nutrients. The influence of soil organic matter on availability of plant nutrients has been reviewed (Flaig et al., 1978; Flaig, 1982; Stevenson, 1982).

The results of long-term manurial experiments conducted at different locations in India are summarized in Table 6; they indicate an appreciable increase in soil organic carbon content due to continued application of FYM for several years. Addition of cattle manure resulted in a considerable increase in N content (0.029%) in soils of the new manurial experiment, whereas only a marginal increase in N content (0.003%) was observed in the old manurial experiment over the initial soil N levels. Increased cation exchange capacity of the soil was also observed with basal dressing of cattle manure compared with the unmanured controls (Krishnamoorthy and Ravikumar, 1973). In the long-term manurial experiments, the highest N buildup was observed with application of FYM and the optimal NPK dose (ICAR, 1986). An appreciable increase in organic carbon and nitrogen content in the soil was found after the harvest of a groundnut crop in which wheat straw had been incorporated (Wani and Shinde, 1980). Addition of unhumified dung in soil depressed N mineralization initially, but after 105 days, N mineralization increased (Bhandari et al., 1972). Dhar (1965) and Dhar and Arora (1968) noted that organic

Table 6. Organic Carbon Content in Soils With and Without Organic Manure From Various Experiments

Location	Organic Carbon		Remarks	Reference
	Control	With Organic Matter		
	(%)			
Coimbatore OPM	0.12	0.16	During 1953/54 i.e., after 44 years	Krishnamoorthy and Ravikumar (1973)
Coimbatore NPM eastern series	0.25	0.34	After 26 years	Krishnamoorthy and Ravikumar (1973)
Coimbatore NPM western series	0.30	0.49	After 26 years	Krishnamoorthy and Ravikumar (1973)
Bangalore	0.45	0.48	Red loam soil after 9 cropping cycles	ICAR (1986)
Hyderabad	0.82	1.25	Red loam soil	ICAR (1986)
Ranchi	0.38	0.45	Red loam soil	ICAR (1986)
Bhubaneswar	0.59	0.76	Laterite soil after 14 cropping cycles	ICAR (1986)
Palampur	0.83	1.20	Submontane soil after 14 cropping cycles	ICAR (1986)
Pantnagar	0.90	1.44	Foothill soil after 14 cropping cycles	ICAR (1986)
Barrackpore	0.45	0.52	Alluvial soil after 14 cropping cycles	ICAR (1986)
Ludhiana	0.27	0.37	Alluvial soil after 14 cropping cycles	ICAR (1986)
New Delhi	0.52	0.56	Alluvial soil after 10 cropping cycles	ICAR (1986)
Coimbatore	0.37	0.46	Medium black soil after 8 cropping cycles	ICAR (1986)
Jabalpur	0.85	1.25	Medium black soil after 13 cropping cycles	ICAR (1986)

matter is the main source of soil N; it helps in N_2 fixation and also increases the amino acid content. Application of FYM along with NPK also resulted in marginal buildup of phosphorus and maintained the initial level in the soil over treatment with NPK alone (ICAR, 1986).

Microbiological Properties – In general, the level of microorganisms in the soil is positively correlated with the level of organic matter (McCalla, 1959; Russell, 1973). Immediately after incorporation into the soil, plant materials are subjected to the transformation and decomposition processes of the heterotropic microflora, and as shown in Table 7, the population of bacteria, fungi, and actinomycetes will be increased with application of plant residues and FYM (Krishnamoorthy and Ravikumar, 1973; Gaur et al., 1971; Shantaram et al., 1975; Sidhu and Beri, 1986). Similarly, application of FYM to soil was shown to increase the population of cellulose-decomposing *Vibrio* in neutral soils (Jensen, 1931). All forms of organic materials help the N_2-fixing heterotrophs in the soil (Gaur et al., 1968, 1971), and if sufficient time is allowed for their activity, the N content of the soil is increased (Desai, 1933). Desai also observed that FYM prepared from straw fixed N_2 in soil and benefited the plants to a great extent. Application of FYM to sandy soils or Alfisols has been shown to stimulate nitrogenase activity associated with pearl millet and sorghum plants (Wani et al., 1984). Similarly, application of wheat straw at 7 tonnes ha^{-1} prior to sowing increased nitrogenase activity in the maize rhizosphere (Sidhu and Beri, 1986).

Organic amendments generally have an inhibitory effect on the activity of soil-borne plant pathogens responsible for causing root diseases (Ledingham, 1970; James and Bruel, 1962; Goswamy and Swarup, 1971; Gouda and Setty, 1973; and Sitaramaiah and Singh, 1978). The role of plant residues in this respect may be one of the factors that contribute to the beneficial influence of the plant materials on the crop to which they are applied. *Fusarium solani, F. phaseoli* were found to be controlled by adding organic amendments with high C:N ratios, such as mature barley or wheat straw, corn stover, or pine shavings. *Fusarium* root rot of bean was managed by adding barley straw (James and Bruel, 1962), and root rot and pea wilt caused by *F. solani* were controlled by adding millet straw. The population of parasitic nematodes was reduced considerably by the incorporation of wheat straw and other organic amendments (Gaur and Prasad, 1970). However, the addition of plant residue does not always inhibit disease development, and addition of green barley (with higher content of N) was shown to increase the severity of disease (Ledingham, 1970).

Future Research Needs

It is evident that biological N_2 fixation can help sustain soil N fertility and that organic manures can be

Table 7. Effect of Organic Manures on Microbial Population in the Soil

Treatment	Bacteria	Fungi	Actinomycetes	*Azotobacter*	*Rhizobium*	*Nitrosomonas*	*Nitrobacter*	Remarks	References
Control	43×10^5	51×10^2	-	36×10^2	55×10^2	131×10^3	70×10^3	Samples were taken up to 15 cm depth	a
Rice straw at 8 t ha^{-1}	68×10^5	76×10^2	-	50×10^2	74×10^2	256×10^3	125×10^3	Samples were taken up to 15 cm depth	a
Control	3×10^5	76×10^2	3.5×10^5	2.1×10^2	-	-	-	Samples up to 15 cm depth were collected after 40 years of experimentation in old permanent manurial experiment at Coimbatore started in 1909.	b
FYM at 12.5 t ha^{-1} $year^{-1}$	3.0×10^5	141×10^2	5.8×10^5	7.1×10^2	-	-	-		
Control	1.2×10^6	2×10^3	-	-	-	-	-	Samples were collected after 35 years of addition of FYM at 12.5 t ha^{-1} $year^{-1}$ in new permanent manurial experiment.	b
FYM at 12.5 t ha^{-1}	3.2×10^6	6×10^3							

a. Sidhu and Beri (1986).
b. Krishnamoorthy and Ravikumar (1973).

successfully recycled to improve soil productivity. Though awareness of their beneficial effects is evident, gaps remain in understanding the mechanisms by which these two biological resources contribute to soil fertility. The following areas are some that need to be considered in future research.

Biological N_2 Fixation

It is important to work out a strategy for the role of N_2 fixation in relation to the use of chemical fertilizer. In doing so, a prerequisite will be to measure or estimate N gain by plants and soils via N_2 fixation.

The quantity and the pathways by which mineralized legume N is made available to the associated or succeeding crop have not been fully elucidated. It is essential to conduct experiments using ^{15}N-labeled legumes to study the process of decomposition of legume N in the soil and its uptake by plants.

The value of legumes in the plant-soil system has been recognized, but it has usually been discussed from the viewpoint of N economy. The role of legumes in improvement of soil structure and accumulation of soil organic matter is also important and should be investigated.

Organic Manures

Most of the information available on the effects of organic manures on crop yields and soil properties is from one or two crop seasons. However, a practical approach would be to conduct such experiments for longer durations at the same site under different agroclimatic conditions.

The effect of application of fresh organic materials in immobilizing available soil nutrients is mainly derived from the negative effects of plant residues on crop yields. Use of labeled material would provide precise information on immobilization and remineralization of the nutrients.

Mutually complementary or synergistic effects of organic manures and chemical fertilizers need to be studie·' and the abundantly available biomass from naturally growing plants such as water hyacinth, *Parthenium, Lantana, Eupatorium*, etc., needs to be profitably used in agriculture with appropriate management.

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