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Long-term Consequences of Legumes in Rice-Wheat Cropping Systems in the Indo-Gangetic Plain

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ABSTRACT

The region of the Indo-Gangetic Plain emerged as a highly productive rice-wheat system with the advent of high-yielding varieties of both the crops and application of irrigation and large amounts of inorganic fertilizers. Recent studies have revealed difficulties in sustaining the productivity of this system vis-a-vis soil quality. These studies have also emphasized the need to explore possibilities of application of organic manures and inclusion of grain and green manure legumes as components of the system, besides application of necessary doses of inorganic fertilizers. This review mainly encompasses long-term research findings on inclusion of either grain legumes and their crop residues or legume green manures to sustain rice-wheat system productivity and maintain soil quality.

Various studies indicated that legumes such as soybean, fodder cowpea, groundnut, and pigeonpea have significant residual effects [equivalent of up to 60 kg nitrogen (N) ha"^{1}] on wheat grain yield. Addition of legume residues substantially improved soil N availability to subsequent wheat or rice crops due to their low ON ratios and relatively higher degree of N mineralization. Mung bean cultivation during summer and incorporation of residues before planting rice also showed favorable effects on soil N availability and rice yields in a wheat-mung bean-rice system. Such a beneficial effect of mung bean was found to be in the range of 20-60 kg N ha^{-1} at different locations in India. Green manuring with *Sesbania aculeata* gave a response equivalent to 80 kg N ha^{-1} in rice and a residual effect equivalent to 120 kg N ha^{-1} on wheat grain yield. These benefits of green manure legumes in rice-wheat systems varied depending on location. Application of phosphatic fertilizer to wheat was beneficial to subsequent legumes such as groundnut and soybean which have relatively higher nutrient absorption efficiency from soil-derived phosphorus (P) as well as an ability to utilize less soluble Ca-P forms. Legumes cultivation resulted in increased nutrient availability and maintenance of organic carbon content besides a marked increase in grain yields of rice and wheat. Addition of farmyard manure and cereal straw were reported to be beneficial in maintaining organic carbon content in the system. A holistic approach to bridge the gaps in understanding the rice wheat system has been proposed through research on (1) characterization of production

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systems, (2) identifying legumes for sustained productivity of rice-wheat cropping systems in the Indo-Gangetic Plain, (3) application of systems modeling to examine scenarios of long-term effects of legumes in rice-wheat systems, and (4) characterization of non-N effects of legumes.

The Indo-Gangetic Plain (IGP) is an important eco-region covering parts of India, Bangladesh, Nepal, and Pakistan where the rice (*Oryza sativa)* and wheat *(Triticum aestivum)* cropping system is a dominant and very productive system, occupying about 12.1 million ha (Singh and Paroda 1995). Some areas of the IGP (e.g., western Uttar Pradesh in India) were mainly a wheat belt before the green revolution in the late 1960s. Post-rainy season wheat used to be grown after rainy season crops such as maize *(Zea mays),* pigeonpea *(Cajanus cajan),* fodder sorghum *(Sorghum bicolor),* fodder cowpea *(Vigna unguiculata),* and rice. With the advent of high-yielding varieties of wheat and rice in the late 1960s, along with development of irrigation schemes and an adequate supply of major nutrients through fertilizers, the area under legumes and consequently their role as ameliorators of soil productivity diminished. The rice-wheat system became dominant since the late sixties. In Bangladesh, the main cropping system has been rice-based, with rice covering 74.4% of the total cropped area and contributing to 50.8% of agricultural gross domestic product (BBS 1992). Pakistan also experienced an increase in wheat production at a rate of 4.4% per annum in the post-green revolution era, i.e., between 1966 and 1976 (Mohammad Aslam et al. 1993). Yield constraint experiments in irrigated areas of Pakistan have shown yield reductions from 51% to 73% without proper fertilizer use (Bajwa 1984). Increasing costs of fertilizers and non-sustainable productivity of rice and wheat in recent years, despite abundant supply of fertilizers and more remunerative prices for legume grains, has encouraged farmers as well as researchers to reconsider the importance of legumes in rice and wheat systems.

Legumes have played an important role in the Indian agricultural economy in sustaining the productivity of the soil through the centuries (Rachie and Roberts 1974). Abrol and Palaniappan (1988) and Nambiar (1995) cautioned about the non-sustainability of the rice-wheat system due to wide occurrence of multinutrient deficiencies in intensively cropped soils, an overall decline in soil productivity and escalating prices of inorganic fertilizers. They emphasized that there should be an increase in use of farmyard manure (FYM), green manure and other legumes, along with inorganic fertilizers, as a possible means of sustaining the productivity of rice-wheat systems.

A large number of experiments have been conducted to study the effect of green manure and grain legumes in rice-wheat systems, mainly concentrating on short-term effects of legumes on cereal productivity and in a few cases on soil quality aspects such as soil organic carbon, available nitrogen (N), and some physical characteristics. Two detailed reviews on short-term effects of summer/rainy season legumes (Ahlawat et al. 1998) and winter legumes (Saraf et al. 1998) on succeeding cereals in rice- and/or wheat-based systems in the IGP are presented in this volume. However, very few experiments have been conducted to investigate the long-term effects of legumes on the productivity of the rice and/or wheat systems as well as on the quality of soil in the IGP. This review emphasizes the research work in long-term experiments on rice and/or wheat-based systems. It addresses long-term effects of legumes in terms of crop productivity and soil quality in (1) wheat systems, (2) rice systems, and (3) rice-wheat systems.

LEGUMES IN WHEAT SYSTEMS

Effect on System Productivity

A long-term study with a soybean *(Glycine max)*-wheat cropping rotation was carried out by Tandon et al. (1986) over eight years, i.e., 16 crop seasons, at Hawalbagh, Almora (1200 m above mean sea level, northwestern Himalayas, Uttar Pradesh, India). They reported that a wheat grain yield of 2 t ha^{-1} could be sustained every year without application of nitrogenous fertilizer to wheat, when the preceding soybean crop was supplied 20 kg nitrogen (N) + 80 kg phosphorus (P) + 40 kg potassium (K) ha^{-1} along with 10 t FYM ha^{-1}. Addition of NPK + FYM to soybean increased availability of N to the following wheat crop (Table 1). These estimates are at best described as rough estimates, as they are based on many assumptions, e.g., there were no estimates of N losses through leaching and denitrification.

Lal et al. (1978) reported from experiments conducted at the Indian Agricultural Research Institute (IARI), New Delhi, India on the contribution of preceding crops, including two legumes, to the fertilizer N economy of the following wheat crop. Although this was not a long-term study, it is particularly relevant as soybean is gradually replacing other legumes in legume-wheat systems, in areas where soil drainage is a problem. Highest yields of wheat were recorded following a cowpea fodder crop which was significantly better than all other preceding crops tested (Table 2 contains selected data). Without fertilizer application to the wheat crop, yield was low (2.82 t ha^{-1}) after soybean compared to a yield of 4.17 t ha^{-1} after cowpea fodder, suggesting that soybean was not beneficial to the following wheat. Soybean and cowpea fodder crops were fertilized with 20 kg N + 26 kg P ha^{-1}. Wheat grain yield of 4.17 t ha^{-1} obtained without fertilizer application following the cowpea fodder crop was closely comparable with yields obtained either by application of 60 kg N ha^{-1} to wheat after soybean or by application of 120 kg N ha^{-1} to wheat after a maize crop. This indicates a beneficial effect of the cowpea fodder crop equivalent to about 60-120 kg N ha"^{1} to the succeeding wheat depending on the type of legume or cereal with which wheat is rotated. Even at fertilizer application of 60 kg N ha^{-1}, yield of wheat after cowpea fodder was higher than that after soybean or maize. Though the reasons for this beneficial effect of cowpea fodder are not clear, one can postulate that cowpea might have fixed more N_2 than

Table 1: Nitrogen (N)-balance sheet of a soybean-wheat cropping system for all measured sources of N expressed as the total for 16 crop seasons (all estimates in kg ha^{-1})[1].

Treatment[3]	N harvested			N added from measured sources				Total N fixed by soybean[2]	Total N fixed by soybean	Total N harvested as wheat
	Soybean	Wheat	Total	Fertilizer	Compost	Soil reserve[4]	Total	(cumulative)	yr^{-1}	yr^{-1}
Control	486	147	633	–	–	142	142	491	61	18
20 kg N + 80 kg P + 40 kg K ha^{-1}	945	228	1173	160	–	284	444	728	91	28
20 kg N + 10 t FYM ha^{-1}	1247	285	1532	160	400	29	589	942	118	36
20 kg N + 80 kg P + 40 kg K + 10 t FYM ha^{-1}	1503	358	1861	160	400	52	508	1353	169	45

[1]Assumptions made are "on all measurable sources of N".
[2]N fixed by soybean = N harvested (soybean + wheat) - N added (fertilizer + compost + soil reserve).
[3]P = phosphorus; K = potassium; FYM = farmyard manure.
[4]N changes in topsoil (0–15 cm) were considered.
Source: Adapted from Tandon et al. (1986).

Table 2: Grain yield of wheat (t ha^{-1}) as affected by preceding legumes and N fertilization to wheat at the Indian Agricultural Research Institute, New Delhi, India.

Summer crop with fertilizer (N + P kg ha^{-1})	N application (kg ha^{-1}) 0	60	120
Maize (120 + 26)	3.67	4.44	4.18
Soybean (20 + 26)	2.S2	4.30	4.52
Cowpea fodder (20 + 26)	4.17	4.87	4.65
LSD at 5%	0.43		

Source: Adapted from Lal et al. (1978).

soybean thus sparing more soil N for the succeeding wheat compared to soybean.

Multilocation experiments conducted at various locations in Uttar Pradesh, Punjab, and West Bengal by the All India Coordinated Agronomic Research Project (AICARP) during 1986/87 to 1991/92 have clearly shown that yields of wheat were always higher after rainy season grain legumes compared to those after rice (see Ahlawat et al. 1998). This residual effect of preceding legumes on wheat could not be quantified as the wheat crop was grown with recommended fertilizers.

In wheat-growing areas of northern India, pigeonpea has become an important component of the wheat-based cropping systems with the introduction of short-duration pigeonpea. Experiments were conducted at IARI during 1984/85 and 1985/86 to compare the effect of rainy season pigeonpea (as a sole crop) and intercropped summer pigeonpea on following wheat yield (Singh and Mahendra Pal 1989). This study indicated that the rainy season pigeonpea-wheat sequence produced 43% lower total productivity with 50% lower yield of pigeonpea and 15% lower yield of wheat than a summer pigeonpea-wheat system (Table 3). The lower yield of rainy season pigeonpea was attributed mainly to an unfavorable rainy season for pigeonpea thus suggesting a relationship between total biomass of pigeonpea and its residual effect on following wheat. However, availability of irrigation water may be a constraint for growing summer legumes even though the season may be suitable for their growth and productivity.

Table 3: Average productivity of a summer and rainy season pigeonpea-wheat cropping system during 1984-85 and 1985-86 at New Delhi, India.

Cropping system	Grain yield (t ha^{-1}) Pigeonpea	Wheat	Total
Summer pigeonpea-wheat system	2.9	4.1	7.0
Rainy season pigeonpea-wheat system	1.3	3.5	4.8

Source: Singh and Mahendra Pal (1989).

In another study, Gill et al. (1987) observed that in both low and medium P soils the wheat yields (2.7 t ha^{-1} and 3.0 t ha^{-1} respectively) following groundnut *(Arachis hypogaea)* were higher compared to those (2.3 t ha^{-1} and 2.7 t ha^{-1} respectively) following mung bean *(Vigna radiata)* in the third year of rotation. Higher yields of wheat observed in soils of medium P level compared to those of low P level could be attributed to differences not only in N_2 fixation of the legume but also in N mineralization of the legume residues, which is related also to P level of the soil. Nguluu et al. (1997) reported that N mineralization from legume residues with low P concentration was consistently less than from those of higher P concentration.

Productivity of a legume-wheat system was studied by Badaruddin and Meyer (1994) for 3 years at Fargo, North Dakota, USA. Without fertilizer application, wheat grain yield following grain legumes was equivalent to or greater than that following a wheat crop fertilized with 75 kg N ha^{-1} and similar to fallow at the same fertility level. Total-N accumulation by wheat following grain legumes was 9% greater than that following wheat but 13% lower than that following fallow. However, N-use efficiency for wheat following legumes was up to 32% greater than that for wheat following fallow and up to 21% greater than that for continuous wheat. These results indicate that grain legumes should be considered to replace fallow and some N fertilization areas where water is not a constraint, which may be applicable to northeastern India and Bangladesh.

Effect on Soil Quality

Residual Soil N and its Availability

Badaruddin and Meyer (1994) found 28% greater soil nitrate-N level in spring following legumes than that following N-fertilized wheat across three environments. But these nitrate levels after legumes were 43% lower than those following fallow. Singh and Mahendra Pal (1989) reported that in a pigeonpea-wheat cropping system the residual N effect on succeeding wheat was equivalent to 51 kg N ha^{-1} due to summer pigeonpea with different intercrops compared to 20 kg N ha^{-1} in rainy season sown pigeonpea. Various legume intercrops tested with summer pigeonpea had different residual N effects. Dhaincha *(Sesbania aculeata)* intercrop for green manure had a residual N effect of 68 kg N ha^{-1} while fodder cowpea recorded 45 kg N ha^{-1} and mung bean grain recorded 28 kg N ha^{-1} (Table 4). In another

Table 4: Residual effect of preceding legumes on wheat yield expressed as the amount of fertilizer nitrogen (N) needed to give the same yield without a preceding legume.

Preceding crop	Residual effect (kg N ha^{-1})
Summer pigeonpea	51
Rainy season pigeonpea	20
Summer pigeonpea + dhaincha (green manure)	68
Summer pigeonpea + cowpea (fodder)	45
Summer pigeonpea + mung bean (grain)	28

Source: Adapted from Singh and Mahendra Pal (1989).

study with a soybean-wheat system for eight years, soil N was maintained with the application of N + FYM or NPK + FYM only to soybean (Tandon et al. 1986). They estimated that application of fertilizer or fertilizer and FYM to the soybean crop, provided 28 to 45 kg N ha^{-1} every year to the subsequent wheat crop. The soybean crop which did not receive any nutrient inputs had a significantly low residual effect and contributed only 18 kg N ha^{-1} to the succeeding wheat (Table 1). As indicated earlier, these conclusions were based on many assumptions, e.g., N supply from soil reserve was calculated based on N changes in the 0-15 soil depth, but not the full rooting depth. Harsharan Singh et al. (1983) observed more available N in the soil after groundnut (171 kg ha^{-1}) as compared to that after wheat (157 kg ha^{-1}). This was against the initial available N of 161 kg ha^{-1} in soil at the start of the experiment. Wheat received 50 kg N ha^{-1} yr^{-1} in both years while groundnut did not receive any applied N in a groundnut-wheat system. This points out the need to characterize the 'N' and 'non-N' benefits of the legumes on the following cereal crops.

In a study at IARI, Singh et al. (1993) reported that a negative soil N balance of -52 kg ha^{-1} was recorded in pigeonpea-wheat and -91 kg ha^{-1} in sorghum-wheat whereas a positive soil N balance of +37 kg ha^{-1} was recorded in cluster bean *(Cyamopsis tetragonoloba)* -wheat and +31 kg ha^{-1} in black gram *(Vigna mungo)* -wheat. This study indicates both positive and negative effects of different legumes on soil N balance and the reasons for this are not clearly known. These differential effects of legumes may be related to differences in their ability to fix atmospheric N and/or also their ability to influence soil N mineralization. Further, the quality of legume residues in terms of N content, lignin, and polyphenols was not studied and this could be the reason for differential effect of legumes on soil N balance. This aspect needs to be studied in detail for understanding and predicting likely effects of different legumes on the succeeding wheat.

Residual Fertilizer P

Crop recovery of inorganic fertilizer P is often very low and it ranges from 8% to 33% depending upon the nature of crop and soil (Mattingly 1975). Aulakh and Pasricha (1991) studied changes in labile and stable forms of inorganic P and organic P in a semi-arid alluvial soil (Typic Ustisamments) after eight years of annual application of fertilizer P either to one crop or to both crops in a groundnut-wheat rotation. They measured 28% of fertilizer P to be in the labile fraction and 44% of fertilizer P in the semi-labile fraction, when phosphatic fertilizer was applied to both groundnut and wheat. In contrast, significantly higher levels of labile (35%) and semi-labile (46%) fractions of fertilizer P were found when phosphatic fertilizer was applied only to either wheat or groundnut in the rotation. Results of this study suggest that increased rates and frequency of P application tend to enhance the conversion of residual P to stable forms, which are less available to plants. Using crop P uptake and total soil P data from this study, Aulakh et al. (1991) calculated the amounts of applied fertilizer P present in the soil.

Percentage of residual P in soil to the total fertilizer P applied to crops, varied between 33% and 67% for wheat, 82% and 93% for groundnut, and *77%* and 91% for both the crops. They also confirmed that legumes can utilize less soluble P such as calcium-bound P better than cereals and meet their P requirement from soil-derived and residual fertilizer P.

Contrary to these findings, in a relatively shorter-term (3-year) testing of a groundnut-wheat rotation at IARI, there was no response of groundnut yield to residual P resulting from P application to wheat (Gajendra Giri 1993). This phenomenon was attributed to sufficient build-up of P in soil profile. However, the observations of Aulakh et al. (1991) were in concurrence with the findings of Hundal and Sekhon (1976) that legume crops in general can more effectively utilize less soluble calcium-P. Thus, application of P fertilizer to wheat is sufficient in a groundnut-wheat system as groundnut can efficiently utilize residual fertilizer P. Similar high efficiency in absorption of soil P by soybean has been reported by Kalra and Soper (1968).

Organic Carbon

Soil organic matter is significantly correlated with soil productivity. Maintaining soil organic matter, therefore, is of critical importance for sustainable agriculture. There are few reports on the changes in soil organic carbon resulting from long-term legume-wheat rotation. Sharma et al. (1984) reported an increase in organic carbon content of soil in a long-term maize-wheat sequence when the recommended dose of fertilizer was applied. On the contrary, in a long-term experiment on a Fatehpur loamy sand soil (Typic Ustipsament) at the University farm, Ludhiana, India, Sharma et al. (1990) observed a decrease in the organic carbon content after the harvest of pigeonpea (0.31%) and wheat (0.33%) compared to its content at the beginning of the experiment (0.38%). This decrease of organic carbon content after pigeonpea is rather surprising as pigeonpea has been reported to add significant amounts of leaf litter (range 1.4-4.9 t ha^{-1}) to soil during the season (Kumar Rao et al. 1996). However, the organic carbon content was higher under optimum agronomic management conditions which may be related to higher amount of crop residues left behind as reported for a maize-wheat system.

LEGUMES IN RICE SYSTEMS

Effect on Systems Productivity

Some common grain legumes grown in rice-legume systems of the IGP are mung bean, black gram, cowpea, groundnut, chickpea *(Cicer arietinum),* pigeonpea, lentil (*Lens culinaris),* khesari *(Lathyrus sativus),* and soybean. The cool season legumes such as chickpea, lentil, and khesari are grown after the harvest of rainy season rice as sequential or relay crops. Farmers usually harvest the entire above-ground biomass of legumes, i.e., grain for human consumption and residues as animal feed.

Singha et al. (1993) observed significantly higher average rice-equivalent yield in a rice-mung bean-rape seed *(Brassica napus)* sequence (8.19 t ha^{-1}), followed by rice-black gram-wheat (8.06 t ha^{-1}), in comparison with three other rice-based cropping sequences tested for 3 years on a sandy clay loam soil (Ultic Haplustalf) in Assam, India. Irrigated mung bean in northern India, grown with recommended practices for grain production and incorporation of residue, reportedly reduces the N fertilizer requirement of the following rice crop by 20-30 kg N ha^{-1} (Chandra 1988). The benefits of legume residue are attributed both to direct N effects and improvement of soil physical properties.

Effect on Soil Quality

Residual Soil N and its Availability

Recent work at the International Rice Research Institute (IRRI), Philippines indicates that there is a build-up of soil nitrate-N during the fallow period after harvest of rice, which will be lost due to submergence and puddling operations for subsequent rice (Buresh et al. 1993; George et al. 1993). These studies clearly point out that growing legumes or weeds helps to conserve this soil N and it is recycled to rice by incorporating the legume or residues during puddling without much loss.

Soil N status was also improved considerably with green manuring. Bharadwaj and Dev (1985) reported an increase in soil N status following rice harvest where *Sesbania cannabina* was used as a green manure (Table 5). Swarup (1986) studied the effect of green manuring by incorporating *Sesbania aculeata* and submergence for 7 days in sodic soil and reported a significant increase in rice yield compared to that obtained from plot without green manuring and flooding. The green manure contributed 111.6 kg N ha^{-1}.

Table 5: Effect of green manuring with *Sesbania* on the total nitrogen (N) concentration of soil after rice harvest at three different locations in northern India.

	N concentration[1] (%)		
Age of *Sesbania* at incorporation	Kanpur (0.047)	Una (0.056)	Palampur (0.058)
45 days	0.049	0.049	0.061
55 days	0.053	0.059	0.069
65 days	0.055	0.068	0.076
CD at (P = 0.05)	0.008	0.012	0.010

[1] Initial total N concentration for each site is indicated within parentheses.

Source: Bharadwaj and Dev (1985).

Although the direct benefit of green manuring on a following rice crop is well established, long-term effects have not been investigated in detail. Sivaraman (1958) reported from studies conducted in Tamil Nadu, India that increases in rice yields due to green manuring were cumulative and steadily increased each year. He also observed improved rice performance under drought due to green manuring. This may be due to enhanced water-holding capacity of the soil as a result of increased organic carbon due to green manuring.

In general, only small increases in grain yield and savings in inorganic N fertilizer have been reported for tropical dry-sown rice following legumes grown for grain and green manure production. In northern Australia, in rice sown 39 to 75 days before permanent flooding, yields were slightly higher following incorporation of either soybean green manure, soybean residue, mung bean residue, or *Sesbania cannabina* residue than following either fallow or sorghum with incorporation of residue (Chapman and Myers 1987). This work may be relevant to upland rice in India or non-puddled rice in the IGP.

The role of green manure crops and their management in irrigated and rainfed lowland rice-based cropping systems in South Asia was reviewed by Abrol and Palaniappan (1988). Leguminous green manuring or incorporation of legume residues after harvesting grain increased the yield of a subsequent rice crop and reduced the requirement of N fertilizer. Morris et al. (1986) did not detect a residual response of green manure in a second rice crop in 4 years of field research in the Philippines with green manure application averaging 83 kg N ha^{-1} to wet season rice. However, Morris et al. (1989) observed residual effects on the second rice crop only at higher rates of green manure application (98 to 219 kg N ha^{-1}). The saving in N fertilizer by using legume N is frequently referred to as the N fertilizer equivalent. Nitrogen from 50- to 60-day-old green manure (Singh et al. 1990) and from mung bean haulm (Rekhi and Meelu 1983) incorporated one day before transplanting on coarse-textured, non-acid soils in Punjab, India, generally substituted for about an equal or slightly greater amount of urea N. In environments other than northwestern India, the N fertilizer substitution was frequently less than the added green manure N (Sharma and Mittra 1988). The differences in N fertilizer substitution values across environments can be explained on the basis of assumptions on uptake use efficiency of the fertilizer and the mineralization of N from green manure residues. However, detailed studies are needed to understand these processes.

Residual Fertilizer P

Beri and Meelu (1981) suggested that P applied to green manure crops in soils with low P status increased green manure production, N accumulation, and succeeding rice yield more than P applied directly to rice. In P rich soils, legumes are capable of drawing their P requirements entirely from soil P or residual P. Another explanation for beneficial effects of green manure on rice yield is increased mineralization of N in green manure because of increased P content of the green manure (see Nguluu et al. 1997). Ranjan and Kothandaraman (1986) reported increased availability of P from rock phosphate applied to rice with green manuring.

LEGUMES IN RICE-WHEAT SYSTEMS

Effect on Systems Productivity

The genetic improvements in rice and wheat during the 1960s coupled with improved management led to marked improvement in the productivity of the rice-wheat system. Towards the end of 1980s the rice-wheat system had shown signs of decline or stagnation in productivity, despite so called 'optimum management' or there was no response for higher amount of inputs (Abrol and Palaniappan 1988; Bijay Singh 1995; Nambiar 1995). Decline in organic matter and exhaustion of soil nutrients including micronutrients have been attributed as major factors for decline in the productivity of the rice-wheat system. The few long-term experiments conducted for rice-wheat systems demonstrate the stagnation or decline of yields with probable causes, and we propose some clues to overcome those constraints.

Nambiar et al. (1989) while summarizing the long-term experiments reported the superiority of integrated use of organic manures and chemical fertilizers in providing greater stability for crop production. This was the case for a rice-wheat system at Pantnagar in Uttar Pradesh and rice-rice or maize-wheat systems at different locations in India, when compared to use of chemical fertilizers alone at 150% of the recommended rate of NPK. But at Barrackpore in West Bengal, 150% of the recommended level of NPK treatment yielded more rice and wheat than 100% NPK + FYM in spite of the fact that FYM checked the loss of organic matter. This suggests that decline in organic matter may not be the only cause of decreasing productivity; probably deficiency of nutrients other than NPK may not sustain high productivity. Nambiar (1995) has recently updated and summarized the results of long-term experiments from the sustainability point of view and gave details of the experiment at Pantnagar on rice-wheat-cowpea fodder rotation which was started in 1971. The productivity of rice declined sharply after 15 annual rotations. Average grain yield of rice over an initial period of 15 years (1972-86) was 6.2 ± 0.12 t ha^{-1}, whereas a reduction in the average yield to 4.2 ± 0.06 t ha^{-1} was observed during the subsequent five-year period (1987-91). These yields were obtained at recommended rates of mineral N, P, K, and sulfur (S) fertilizers. Similar reductions were also noted with 150% N, P, K, S, and N, P, K, zinc (Zn) treatments. This reduction occurred after 15 annual rotations. An average yield of 4.2 t ha^{-1} could be maintained by applying Zn or FYM. It is not clear whether 4.2 t ha^{-1} yield of rice can be maintained only by addition of Zn along with other recommended major nutrients or by addition of FYM along with other fertilizers. However, it is clear that even a fodder legume such as cowpea could not sustain the productivity of the system, perhaps because of the way it was managed, i.e., removal of above-ground biomass from the field. On the other hand, a green manure legume grown and incorporated in situ in place of fodder cowpea might have sustained the productivity of the rice-wheat system. However, the initial productivity of wheat was maintained with recommended doses of mineral NPKS fertilizers throughout the experimental period (1972-91).

A long-term experiment at Ludhiana, India has clearly indicated that the adverse effects of wheat and rice straw residues can be effectively overcome by combined incorporation of green manure with crop residues (Table 6). Green manuring and addition of either rice straw or wheat straw significantly increased rice grain yield but not wheat grain yield. Application of green manure alone produced higher rice grain yield compared to application of 150 kg N ha^{-1} along with wheat straw. Growing a green manure legume crop between wheat and rice in a rice-wheat rotation in northern India requires irrigation (see Lauren et al. 1998 for more information). Short-duration mung bean (60-70 days) or fodder cowpea is grown by some farmers during the summer months after wheat harvest and before the rainy season rice.

Table 6: Effect of crop residue management and green manuring on soil organic matter content and yields of crops in rice-wheat rotation at Ludhiana, India.

Treatment[2]	Rice grain yield[1] (t ha^{-1})	Wheat grain yield[1] (t ha^{-1})	Organic carbon after rice (1993) (g kg^{-1})
Control	4.0	4.2	3.5
120 kg N ha^{-1}	5.8	4.2	3.7
150 kg N ha^{-1}	6.2	4.2	3.8
Green manure (GM)	6.2	4.3	4.1
GM + wheat straw	6.4	4.4	4.7
GM + rice straw	6.5	4.4	5.0
Wheat straw + 150 kg N ha^{-1}	5.7	4.2	4.9
LSD (P = 0.05)	0.45	-	0.7

[1] Average of 1988 to 1993.

[2] Control = No nitrogen (N); urea was applied to all GM treatments to make N addition through GM + urea = 150 kg N ha^{-1}.

Source: Meelu et al. cited by Bijay-Singh (1995).

Rekhi and Meelu (1983) reported that mung bean grown as a summer crop in a wheat-mung bean-rice rotation for 3 years contributed an amount of N equivalent to 60 kg urea N ha^{-1} to the rice crop from the addition of mung bean residue after the harvest of grain (Table 7). The amount of N added to soil in the form of residue was 100 kg N ha^{-1}. Mung bean also contributed grain yield of 0.86 t ha^{-1} to the total productivity of the system. The authors ascribe the beneficial effects of mung bean straw incorporation not only as mere addition of N but also to its favorable effect on the availability of soil N and probably on soil physical properties. Kulkarni and Pandey (1988) also reported the beneficial effects of inclusion of mung bean in a rice-wheat sequence from experiments conducted by the AICARP during 1982-85 at 3 locations, i.e., Ludhiana, Masodha, and Navasari. Mahapatra et al. (1974) and Ali (1992) reported that summer mung bean in

Table 7: Effect of mung bean straw and fertilizer nitrogen (N) on following rice yield grown as part of wheat-mung bean-rice sequence.

Mung bean straw	Fertilizer N ($kg\ ha^{-1}$)	Rice grain yield ($t\ ha^{-1}$)[1]
Removal	0	3.17
	60	5.21
	120	7.09
Incorporation	0	6.46
	60	7.37
	120	8.53
CD at (P = 0.05)		0.51

[1] Mean of 3 years.

Source: Rekhi and Meelu (1983).

the rice-wheat-mung bean sequence gave grain yields between 0.5 and 1.0 t ha"[1] and a contribution of fertilizer N equivalent of 25-40 kg N ha^{-1} to the following rice crop. Hegde (1992) summarized the multilocational trials conducted during 1987-90 and reported that incorporation of mung bean residue to soil after removal of grain was as effective as green manuring in improving the productivity of the rice-wheat system.

From the above reports the beneficial effect of mung bean in rice-wheat systems was 20-60 kg N ha^{-1}. This wide range could be due to variation in uptake use efficiency of the fertilizer and the uptake use efficiency of the legume residues among locations. In some cases, the fertilizer equivalent value may seem quite high, but may be only attributed to a relatively small amount of actual N, because the uptake efficiency of the fertilizer may be very poor (because of leaching or other losses). The uptake efficiency of legume residues will be a product of the degree of N mineralization and the uptake process. It may be the uptake process that could be the key, that is, mineralization may not be so much but the plant might be getting it all. Detailed studies are therefore needed to characterize the beneficial effects of mung bean in rice-wheat system.

Effect on Soil Quality

Residual Soil N and its Availability

Leguminous green manures incorporated before cropping with lowland rice can increase grain yield of a following wheat (Tiwari et al. 1980; Sharma and Mittra 1988). Generally a build-up of soil nitrate may take place after the harvest of wheat and before the planting of rice. Thus growing a legume green manure or short-duration legume may help to conserve soil N.

In a rice-wheat rotation in India, application of 80 kg urea N ha^{-1} to rice had no effect on wheat yield, but application of 40 kg N ha^{-1} as *Sesbania aculeata* combined with 40 kg urea N ha^{-1} to rice increased wheat yield by 0.7 t ha^{-1} and 0.6 t ha^{-1} in two consecutive years (Mahapatra and Sharma 1989). The authors speculated that the application of green manure to rice, besides providing N, might have improved the soil physical conditions after rice and thus allowed better growth of wheat on the soil that was puddled for rice production.

In another study, Beri and Meelu (1981) observed yield benefit of rice equivalent to 60 kg N ha^{-1} in a rice-wheat-legume system with *Sesbania aculeata* as green manure (Fig. 1). However, there was no residual effect on

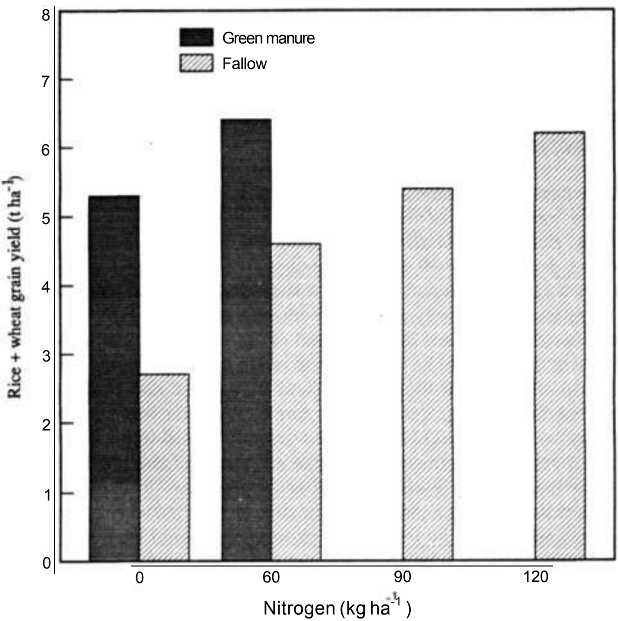

Figure 1: Effect of green manuring and fertilizer nitrogen (N) on rice + wheat yields and N economy in rice-wheat system.
(Source: Beri and Meelu 1981).

yield of a succeeding wheat crop. Tiwari et al. (1980) studied the effect of green manuring on rice-wheat and found a response equivalent to 80 kg N ha"[1] in rice, i.e. a rice grain yield = 4.9 t ha^{-1} was obtained either by application of 40 kg N + green manure or by application of 120 kg fertilizer-N ha^{-1}, and a residual effect equivalent to 120 kg fertilizer-N ha^{-1} in the succeeding wheat grain yields (Table 8).

Organic Carbon

The data from long-term experiments on the rice-wheat system started in 1971 at Barrackpore and Pantnagar clearly indicated a decline in soil organic

Table 8: Effect of green manure (GM) and fertilizer nitrogen (N) on grain yield of rice and residual effect on grain yield of following wheat in rice-wheat system.

	Rice grain yield (t ha^{-1})		Residual effect on wheat grain yield (t ha^{-1})	
N (kg ha^{-1})	Fallow	Green manure	Fallow	Green manure
0	2.37	3.85	1.67	2.31
40	4.04	4.91	1.71	2.78
60	4.63	5.27	1.88	3.18
120	4.98	5.37	2.27	3.35
Mean	4.01	4.85	1.88	2.98
CD at 5% for				
N level (N)			0.5	0.12
GM			0.36	0.09
GM*N			0.71	0.17

Source: Tiwari et al. (1980).

matter after 16 years (Nambiar et al. 1989) in spite of the system receiving recommended application of NPK fertilizers. Organic carbon content in the soil was reduced by 30% at Barrackpore and 38% at Pantnagar compared to the values at the beginning of the experiment (Table 9). The initial level of organic carbon in soil was maintained at Pantnagar by the combined application of NPK fertilizer and FYM, but it could not be maintained at Barrackpore. Frequent tillage and alternating wetland (rice) and upland (wheat) conditions might have lead to rapid decomposition of soil organic matter in the system at Barrackpore.

Table 9: Changes in soil organic carbon content under different rice-wheat-based cropping systems in India as influenced by fertilizer and farmyard manure (FYM) during 1971-1987.

	Organic carbon content (g kg^{-1})	
Treatment[1]	Rice-wheat-jute at Barrackpore	Rice-wheat-cowpea fodder at Pantnagar
50% NPK	5.0	9.7
100% NPK	4.4	10.3
150% NPK	5.0	14.6
100% NPK + FYM	*6.2*	15.6
Control	4.2	7.0
Initial status	7.1	14.8

[1] Percentage of recommended application rate of fertilizer [nitrogen (N), phosphorus (P) and potassium (K)].

Source: Adapted from Nambiar et al. (1989).

Gaur et al. (1984) found that application of FYM or compost was the best strategy for maintaining organic matter in soils. However, the scarcity of

FYM is posing a problem as increased dependence on mechanization reduced cattle population in several areas of the IGP. Use of crop residues is a second option. During earlier years, i.e., before mechanization, cereal residues were used as cattle feed but now many farmers burn them instead of incorporating them in the field for the sake of easy farm operations. Use of green manure is a third option to improve soil organic matter. Because of their succulent nature, low C:N ratio, and low lignin content of legume green manures, they decompose rapidly when incorporated in the soil and only a small quantity of content is converted into stable soil organic carbon (Yadvinder Singh et al. 1992). Boparai et al. (1992) observed that after 3 years of rice-wheat rotation organic carbon content of the unamended soil decreased from 1.9 g kg^{-1} to 1.5 g kg^{-1}, whereas green manure helped to maintain it at the initial level. Bharadwaj and Dev (1985), Sharma and Mittra (1988), and Meelu et al. (1991) observed an increase in the soil organic carbon content ranging from 0.4 g kg^{-1} to 1.0 g kg^{-1} due to green manuring of rice.

Yadvinder Singh et al. (1988) reported significant build-up of soil organic matter due to incorporation of rice and wheat straw into the soil compared to when removed or burnt but the yields of rice and wheat yields were lower despite improved soil physical conditions. The authors attribute the decline in rice and wheat yield in cereal residue incorporated treatments to immobilization of soil and fertilizer N. However, additions of either wheat straw or rice straw improved organic carbon.

CONCLUSIONS

Even though there were not many long-term experiments involving legumes in rice and wheat systems in the IGP, the available information clearly indicates that the rice-wheat system is unsustainable in terms of inorganic nutrient inputs alone. Integrated nutrient management involving application of both inorganic fertilizers and organic manures may make the system more sustainable. Green manure legumes or crop residues of grain legumes play an important role as a complete or partial source of organic manure to stabilize the rice-wheat system where FYM is becoming scarce. Legumes (green manures or grain legumes) not only improve and stabilize the productivity of rice and wheat but also improve the quality of soil which will have a positive bearing on the sustainability of the system. The beneficial effects of legumes in rice-wheat system depend on the region, although the reasons for this variation are not readily apparent. Evidence indicates that legumes need to be introduced in rice-wheat system in order to maintain or improve soil organic carbon and soil total N and its availability. Legumes enhance the availability and efficient utilization of residual P which is otherwise not available to cereals. Efforts have not been made to characterize rice-wheat systems of the IGP with the aim of identifying areas suitable for including a particular legume (grain, green manure, or forage) into the cereal dominated system. Farmers' acceptance of a legume into a rice-wheat system (a rainy season legume in place of rice or a postrainy season legume in place of wheat or a summer legume after wheat but before rice) will depend largely on the economic returns compared to the existing system.

FUTURE RESEARCH AREAS

Results from a few long-term experiments have shown the beneficial effects of legumes on the productivity of the rice-wheat system as well as on some aspects of soil quality such as soil organic matter, soil N, and P availability. Although legumes were reported to have beneficial effects on the following wheat crop, both positive and negative soil N balances following different legumes were indicated. Thus, there is a need to characterize the 'N' and 'non-N' benefits of the legumes on the following cereal crops. Since phosphate fertilizers are a costly input in agriculture, it is important to calculate the P requirements of the rice-wheat system following inclusion of a legume in the system. This might result in saving of fertilizer P in the rice-wheat system.

There is a need to study the mineralization of different legume residues and how that matches the N and P requirements of the following rice or wheat crop at various growth stages. In this context it is important to study the relationship between the mineralization and chemical composition (quality) of the legume residues (N, P, K, lignin, soluble carbon and soluble polyphenols) vis-a-vis the soil type and the environment. Standardized methods for these analysis are recommended (Palm and Rowland 1997). Fertilizer equivalency or nutrient substitution values of legume residues can then be determined and related to the quality of the material. Such information could be obtained through a combination of laboratory incubations and field trials. Incubations establish the amount of different organic materials needed to obtain similar soil available nutrient levels for a given amount of fertilizer. Field trials can test recommendations from the incubations on different soils and climates and models can be used to extrapolate to other types of organic materials and environments. Field trials usually relate the yield obtained from organic inputs to the yields obtained from an inorganic fertilizer response curve. One must be certain of the limiting or co-limiting nutrients of a particular soil and then decide if the trial will assess the nutrient equivalency of one or more nutrients. Once fertilizer equivalency values have been established for different groups of plant materials, trials can determine the substitutive effect of organic material of different quality at different proportions of organic to inorganic sources. Unlike an inorganic fertilizer N source, the legume residues will have different residual effects which have to be quantified over a number of cropping seasons.

Gaps in knowledge about the long-term effects of legumes on pests and diseases affecting the productivity of the rice and wheat system do exist. Information is also lacking about the long-term effect of legumes in rice-wheat systems on soil quality indicators such as soil structure, aggregation, bulk density, water-holding capacity, infiltration, soil erosion, and biological activities. A holistic systems approach involving multi-disciplinary research teams should be encouraged to initiate long-term studies to evaluate the effects of legumes in sustaining the productivity of the rice-wheat cropping system in IGP. Integrating the numerous and complex roles of legumes in soil fertility and crop growth might be assisted by simulation models. Models, however, are only as good as the data that are used for constructing them, and knowledge gaps still exist on the role of different legumes (green manure, grain, and forage legumes) and their interactions with factors such as inorganic fertilizers, in modifying soil nutrient availability or soil health of rice and wheat systems. More controlled experiments are needed that can be used for developing and validating models. Once these models exist, they can assist in evaluating legumes in rice and wheat systems.

Cropping systems models such as APSIM (McCown et al. 1996) and DSSAT (Tusji et al. 1994), simulate short-term crop production but are limited in their ability to model residue decomposition and soil organic matter dynamics. There seem to have been no attempts to merge the detailed soil process models with the crop models that are better at simulating crop growth and yield. Van Noordwijk and Van de Geijn (1996) also stress that models that include root processes are essential for simulating nutrient dynamics. Cropping systems modeling studies should be initiated to explore various long-term options on including legumes in rice-wheat systems for farmers of the region. Despite these gaps in our knowledge, legumes have generally been found to be beneficial in rice-wheat cropping systems. However, farmers are not enthusiastic to include legumes in rice-wheat cropping systems probably because of uncertain returns from legumes compared to the two cereals. There is a need to identify high-yielding, short-duration grain legumes with minimal risk of crop failure. For example, if insect pests could be adequately controlled, extra-short-duration pigeonpea could be a candidate due to its high biomass production, grain yield potential, N_2 fixation potential, and leaf fall. Policy changes would also be required to encourage legume cultivation in rice-wheat systems for improving the sustainability of the system (Joshi 1998).

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