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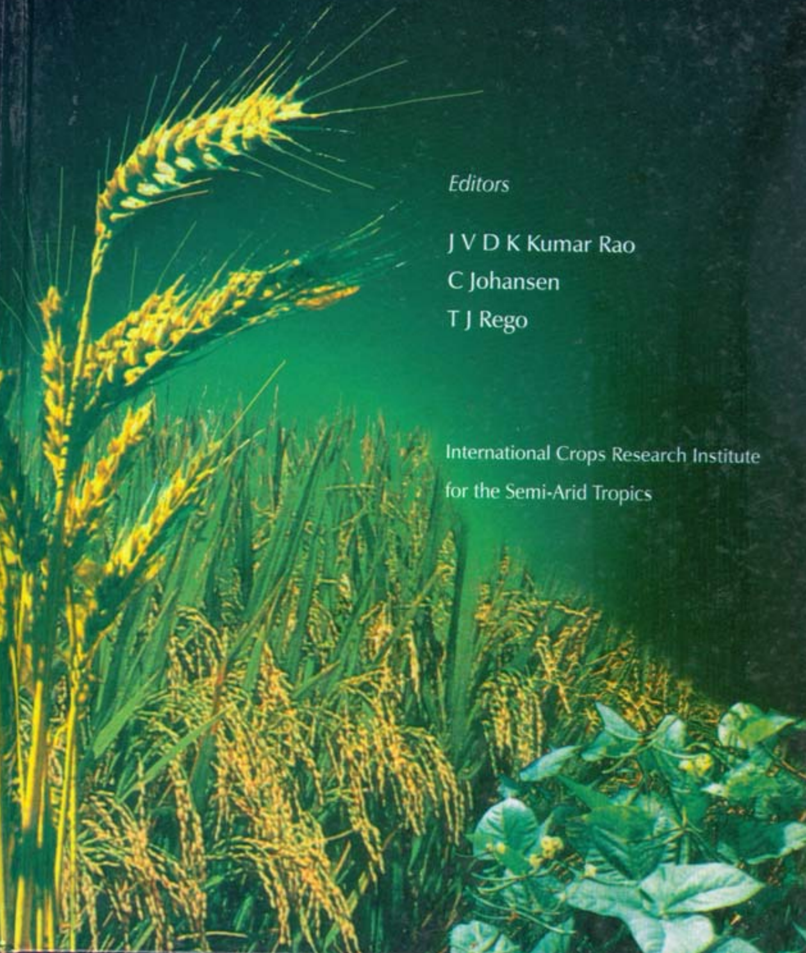

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Foreword

Cereals are important in the economy of many developing countries. Rice and wheat are the principal food crops for the majority of the world's people; their production has to increase steadily in order to meet global demand. Although, the "green revolution" dating from the 1960s has more or less allowed demand for total food grains in South Asia to be met by internal production, this has resulted in imbalances in production between crops and there are now questions about the ability of the major production systems and particularly rice-wheat systems, to meet the ever-increasing demands for food grains. There are increasing concerns that high input rice-wheat cropping rotations in the Indo-Gangetic Plain (IGP) are reaching productivity limits, and further that the edaphic resource base is under threat due to various degradation processes such as declining soil organic matter levels, increasing salinity, buildup of pests, diseases and weeds, etc. Before the 1960s, various types of legumes were regularly included in crop rotations in the IGP, but with the advent of green revolution technologies, it was perhaps considered that the ameliorative effects of legumes in rotation were no longer important. Many of the maladies associated with continuous rice-wheat cropping are yet to be precisely diagnosed (e.g., soil chemical, physical, and biological factors) and so non-legume alleviatory measures are difficult to formulate. The alleviatory effects of legumes on subsequent crops in the Asian region have long been realized and to some extent documented, even if precise mechanisms of legume effects have not usually been characterized.

This book is a product of the collaborative research project on "Legume-based technologies for rice and wheat production systems in South and Southeast Asia", a part of the Natural Resources Management Program of ICR1SAT. The component of the project focussing on the IGP links closely with the Rice-Wheat Consortium (RWC) for the Indo-Gangetic Plain. The project provides legume perspective input for the RWC. It thereby links with other International Agricultural Research Centers (e.g. IRRI, CIMMYT, IIMI) and Advanced Research Institutes (e.g., Cornell University) involved with the RWC. We acknowledge the support of the European Union (EU), Government of Japan, and Asian Development Bank towards this research project.

I hope the information compiled in the book is useful to understand the present status and role of legumes in rice- and wheat-based systems of the

IGP and would pave the way for more focussed work aimed at improving the sustainability of the rice- and-wheat-based systems of the IGP.

May 1998

Shawki M. Barghouti
Director General

Introduction

Among various agricultural production systems, the various rice and wheat cropping systems in the Indo-Gangetic Plain covering Bangladesh, India, Nepal, and Pakistan are both agroecologically and socioeconomically important. There have been expressions of concern for long-term sustainability of rice- and wheat-based systems, as for other repetitive cropping systems. Population growth rates near 2% per annum for the present human population in Asia approaching 3 billion, necessitates ever-increasing production of these staple grains (>2.5% p.a.). This is imposing an inevitable threat to the natural resource base, even in traditionally well-endowed areas and examples of adverse consequences of continuous cereal cropping are being increasingly documented. A closer examination of cropping sequences is needed if productivity of rice and wheat is to be maintained and further increased. In this context, the well-known ameliorative effects of legumes in crop rotations need close attention in relation to the sustainability of rice and wheat production systems.

A regional workshop entitled "Residual effects of legumes in rice and wheat cropping systems of the Indo-Gangetic Plain" was organized at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India during 26-28 August 1996 with the following objectives: (1) to collate and interpret existing information on legume residual effects on subsequent crops for the region; (2) to formulate future research needs; and (3) to present the outcome of the workshop in the form of a book. About forty participants representing the Rice-Wheat Consortium member countries (Bangladesh, India, Nepal, and Pakistan), Cornell University (USA), Vietnam, and ICRISAT participated in the workshop. There were presentations on biological nitrogen fixation and residual effects of legumes (winter, summer, and rainy season grain legumes; forage and green manure legumes), and management and prospects of legumes in member countries of the Rice-Wheat Consortium. The group discussed research needs on summer and winter grain legumes, forage legumes, and green manure legumes—constraints to adoption of technologies for including legumes, knowledge gaps and researchable issues, target regions, and important cropping systems. The research needs were then prioritized. Organizations that could be involved in undertaking the prioritized research work were identified. Close linkage with the Rice-Wheat Consortium was favored by the participants for implementation of the proposed research. This book is based on the papers presented and the deliberations of the workshop.

We thank all the participants of the workshop for active involvement and developing recommendations of the workshop. Our special thanks are due to the discussion leaders of the three different groups, namely, Dr M. Ali of the Indian Institute of Pulses Research, Kanpur, India; Dr. R.L. Yadav of the Project Directorate of Cropping Systems Research, Modipuram, India; and Dr. R.J.K. Myers of the Natural Resources Management Program, ICRISAT. We sincerely thank the contributors of the chapters and the reviewers for their efforts to improve upon presentation of the chapters.

We are grateful to the Asian Development Bank for financial support in the preparation and publication of this book. The workshop and ICRISAT staff costs were supported by contributions of the Government of Japan and the European Union to ICRISAT.

We thank Mr. A. Sudhendra and Mr. Y. Prabhakara Rao for their assistance in preparing the manuscript. We are also most appreciative of the technical editing input provided by Mrs. V.K. Sheila. We thank M/s. Arth Graphics, Secunderabad, for the cover design.

We sincerely thank ICRISAT for overall support for the workshop and its outcome.

The Editors

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Biological Nitrogen Fixation and Residual Effects of Legumes

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Performance of Grain Legumes in the Indo-Gangetic Plain

P. K. Joshi[1]

ABSTRACT

The study is an attempt to assess the temporal and spatial changes in the status of grain legumes and examine their role in influencing use of inorganic sources of nitrogenous fertilizer, and effects on productivity growth of rice and wheat. The study is confined to the Indo-Gangetic Plain (IGP) region of Bangladesh, India, Nepal, and Pakistan. Data on various aspects were collated from several published sources from 1980/81 to 1992/93. Compound growth rates were computed for production, area, and yield of major grain legumes to examine sources of growth in their production. Traditionally, legumes were an important element of the cropping systems in the IGP. With the introduction of improved varieties *of* rice and wheat, legumes were replaced to a large extent. Their area has declined in Bangladesh and India, but slightly increased in Nepal and Pakistan. In India, area under major legumes declined in all the states incorporating the IGP. However, there was an increasing trend in the yields of important legumes. Despite an increase in yields, decline in legumes area adversely affected their production. Based on case studies in Nepal and Bangladesh, and aggregate analysis in Indian states, it was observed that residual effects of legumes result in saving of nitrogenous fertilizer and improving the productivity of subsequent rice crops. Despite their role in improving soil fertility, grain legumes are less preferred due to low profitability, high risk, and lack of adequate markets and knowledge of recently developed and released improved varieties.

INTRODUCTION

Traditionally, legumes have been considered important elements of cropping systems in the IGP. They were popular because of their importance as a source of protein and ability to fix atmospheric nitrogen (N) and thus improve soil fertility. With the introduction of irrigation and due to high profitability of alternative sources of soil nutrients in the form of inorganic

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fertilizers in the mid-1960s, legumes were replaced or relegated to marginal lands. During the late 1960s and early 1970s, a large area under legumes in the Indo-Gangetic Plain (IGP) was substituted by high-yielding varieties of rice *(Oryza sativa)* and wheat *(Triticum aestivum).* The new technology of rice and wheat, substantially changed the agricultural scenario and largely contributed to increase in agricultural production in the IGP. With the passage of time, excessive use of chemical fertilizers and irrigation in rice and wheat to maintain their productivity has created an imbalance in soil fertility and threatened the sustainability of the most productive food grain belt in South Asia (Hobbs and Morris 1996). Legumes are an effective source of reversing the process, and can contribute significantly to achieving the twin objectives of increasing productivity and improving the sustainability of the rice- and wheat-based cropping system in the IGP (Ahlawat et al. 1998; Lauren et al. 1998; Yadav et al. 1998). It is, therefore, important to diagnose and characterize the dynamics of the performance of legumes in the IGP. Such an analysis will provide information to prescribe appropriate policies and strategies for inclusion of legumes in the existing cropping system.

The present study is an attempt in this direction. The specific objectives of the study are to (1) assess the temporal and spatial changes in the status of legumes in the IGP; (2) investigate sources of growth in legumes production in the IGP; and (3) examine the role of legumes in application of N fertilizer and productivity growth of rice and wheat.

METHODOLOGY

Legumes are grown for grain and forage production, and for green manuring. Due to a limitation of accessible data, the study is confined to grain legumes. Important legumes which are included in this study are black gram *(Vigna mungo),* chickpea *(Cicer arietinum),* mung bean *(Vigna radiata),* groundnut *(Arachis hypogaea),* lentil *(Lens culinaris),* pea *(Pisum sativum),* common bean *(Phaseolus vulgaris),* khesari *(Lathyrus sativus),* pigeonpea *(Cajanus cajan),* and soybean *(Glycine max).* The study is confined to the IGP, covering the administrative boundaries of Bangladesh, Nepal, Pakistan, and parts of India including Bihar, Haryana, Punjab, Uttar Pradesh, and West Bengal. Data on area, production, and yield of legumes were collated for selected countries and states in India from 1980/81 to 1992/93 from various published sources (Government of India 1994; FAO 1995). Data was also collected on use of N fertilizers and yields of rice and wheat from the Fertilizer Association of India and the Directorate of Economics and Statistics, Government of India, New Delhi, India.

To assess the spatial and temporal changes in the status of legumes, the share of different legumes in the grosscultivated area was computed for triennial averages ending 1982/83,1986/87, and 1992/93. Compound growth rates in area, production, and yield of all selected legumes were computed to examine sources of growth during three periods: (1) 1980/81 to 1985/86, (2) 1986/87 to 1992/93, and (3) 1980/81 to 1992/93.

LEGUMES IN THE IGP

Grain legumes occupied slightly less than 8 million ha in the early 1990s in Bangladesh, Nepal, Pakistan, and the five states of IGP in India. About 1 million ha under grain legumes was substituted by other crops during the past decade. The decline in area was attributed to relatively higher profitability of rice and wheat (Malik 1994). India grows the largest proportion of about 65% of the total grain legumes area in the IGP, followed by Pakistan (20%).

The major grain legumes are chickpea in India and Pakistan, lentil and khesari in Bangladesh, and lentil, khesari, and chickpea in Nepal. While area under chickpea in India declined during 1981-83 to 1990-92, it has marginally increased in Pakistan (Table 1). In India, area under lentil, peas

Table 1: Average area ('000 ha) of principal legumes in countries located in the Indo-Gangetic Plain.

Crop	Year	Bangladesh	India	Nepal	Pakistan
Black gram	1981-83	NA[1]	480	Neg.[2]	70
	1985-87	70	430	Neg.	76
	1990-92	67	514	18	76
Chickpea	1981-83	124	2760	54	958
	1985-87	106	2355	29	1043
	1990-92	97	1787	27	1041
Khesari	1981-83	202	NA	50	Neg.
	1985-87	232	NA	40	Neg.
	1990-92	242	NA	40	Neg.
Groundnut	1981-83	25	250	Neg.	59
	1985-87	29	185	Neg.	62
	1990-92	39	174	7	89
Lentil	1981-83	274	627	103	78
	1985-87	223	735	107	62
	1990-92	209	807	120	63
Mung bean	1981-83	NA	357	Neg.	NA
	1985-87	60	411	Neg.	NA
	1990-92	*55*	384	Neg.	NA
Peas and beans[3]	1981-83	213	291	21	308
	1985-87	171	320	25	327
	1990-92	160	400	27	358
Pigeonpea	1981-83	NA	643	Neg.	Neg.
	1985-87	6	668	16	Neg.
	1990-92	6	640	18	Neg.
Soybean	1981-83	NA	145	10	4
	1985-87	NA	21	16	5
	1990-92	NA	22	21	2

[1]NA = data not available.
[2]Neg. = area under crop is negligible.
[3]Separate data for peas and beans are not available.
Source: FAO (1995); Government of India (1994).

and beans has increased, while that of groundnut and soybean has declined. Pigeonpea area has remained stable in the Indian region of the 1GP. In Nepal, area under lentil, peas and beans, and soybean has shown a marginal increase.

In the Indian region of the IGP, area under grain legumes has been declining in all the states (Table 2). Uttar Pradesh has the largest share (about 60%) of total grain legumes area, followed by Bihar (about 21%). In Uttar Pradesh, chickpea, pigeonpea, and lentil are the prominent grain legumes occupying about 70% of the total legumes area in early 1990s. Although chickpea is still the principal grain legume, its area (36%) has substantially declined during the 1980s. On the other hand, area under lentil, black gram, and peas and beans has increased during the same period.

Table 2: Average area ('000 ha) of principal legumes in the Indian states of the Indo-Gangetic Plain.

Crop	Year	Bihar	Haryana	Punjab	Uttar Pradesh	West Bengal
Black gram	1981-83	118.5	10.1	18.3	205.2	1292
	1985-87	100.6	3.4	11.2	221.6	93.4
	1990-92	88.2	1.6	7.1	290.5	126.6
Chickpea	1981-83	186.8	764.3	208.3	1524.4	77.9
	1985-87	187.2	522.7	96.4	1481.5	68.2
	1990-92	146.5	447.3	37.6	1133.7	21.2
Mung bean	1981-83	161.2	5.2	20.1	148.3	22.0
	1985-87	190.9	*6.5*	44.5	139.0	30.5
	1990-92	214.9	8.8	47.3	97.9	14.8
Groundnut	1981-83	5.9	7.0	84.3	249.6	1.9
	1985-87	5.1	5.9	39.7	121.0	13.2
	1990-92	5.0	2.2	11.0	135.0	20.6
Lentil	1981-83	172.9	24.1	18.1	331.1	81.3
	1985-87	168.3	21.6	11.5	448.5	86.0
	1990-92	179.7	15.1	7.5	541.7	63.3
Peas and beans[1]	1981-83	31.5	7.9	4.0	242.6	4.0
	1985-87	34.9	7.3	4.3	268.5	6.0
	1990-92	33.3	3.6	4.0	352.8	4.5
Pigeonpea	1981-83	87.6	8.1	15.9	506.1	25.1
	1985-87	78.4	31.7	33.1	514.5	9.6
	1990-92	65.5	52.4	12.3	506.2	4.9
Soybean	1981-83	Neg.[2]	Neg.	Neg.	144.5	Neg.
	1985-87	Neg.	Neg.	Neg.	127.2	Neg.
	1990-92	Neg.	Neg.	Neg.	21.6	Neg.
All legumes	1981-83	1278.8	829.7	372.9	3355.2	441.8
	1985-87	1209.8	600.8	242.1	3330.6	391.8
	1990-92	1094.0	531.6	127.9	3084.4	311.3

[1]Separate data for peas and beans are not available.

[2]Neg. = area under crop is negligible.

Source: Directorate of Economics and Statistics, Government of India: compiled from various issues (1981 to 1996) of the Agricultural Situation in India.

In Bihar, mung bean (20%), lentil (17%), and chickpea (13%) together occupy about half of the grain legumes area. Among all grain legumes, area of only mung bean and lentil has increased. The increase in area under mung bean is higher than that of lentil. In Haryana, chickpea and pigeonpea occupied 94% of the total grain legumes area in early 1990s. Area under pigeonpea and mung bean has increased during the early 1990s as compared to the early 1980s. Pigeonpea area has increased by about six-fold from 8.1 thousand ha in early 1980s to more than 50 thousand ha in early 1990s. It is becoming important in water-scarce regions.

Grain legumes are minor crops occupying less than 4% of the gross cultivated area in West Bengal and 2% of that in Punjab. In West Bengal, however, black gram and lentil are still the main grain legumes, although there is a sharp increase in groundnut area. In Punjab, chickpea and mung bean are the major grain legumes. While chickpea area has sharply declined in the state, mung bean has gained importance; its area has increased from 20 thousand ha in the early 1980s to about 47 thousand ha in the early 1990s.

In summary, the area under prominent legumes is declining in major legume-producing regions. The declining trend has been forced because of several abiotic, biotic, and socioeconomic constraints in the IGP. Some important socio-economic constraints are:

- Legumes are relatively less profitable than rice and wheat in the IGP under the existing policy regime and technology options (Malik 1994; Joshi et al., in press).
- Production of legumes is relatively more risky than that of rice and wheat. The price and yield risks of legumes are much higher than those of rice and wheat (Joshi and Pande 1996).
- Markets for legumes are thin and fragmented in comparison to rice and wheat which have assured markets (Byerlee and White 1997).
- Price spread (or the market margin) for legumes is much higher than that for rice and wheat due to higher post-harvest costs. The share of farmers in consumer's costs in case of legumes is much lower than that for rice and wheat (Joshi and Pande 1996; Joshi et al., in press).
- Legumes are more prone to post-harvest losses than rice and wheat (Kumar et al., in press).
- Farmers lack knowledge about the recently developed and released improved varieties of pigeonpea and chickpea. In a survey conducted in northern India and the Terai region of Nepal, it was observed that farmers know little about the improved varieties of short-duration pigeonpea (Pande and Joshi 1995).

GROWTH SOURCES OF LEGUMES

In principle, there are two sources of increasing production of any agricultural cropping enterprise: (1) area expansion, and (2) yield increase. Area expansion is possible through crop substitution and/or utilization of fallow lands. Yields can be increased by adopting improved technologies involving improved cultivars and/or better crop management. To understand the sources of growth in production of different legumes, annual compound growth rates of all selected grain legumes for area, production, and yield in selected states of the Indian region of the IGP during 1980/81 to 1986/87 and 1987/88 to 1992/93 were computed. It was observed that growth in yields of all the selected legumes increased in some states of the IGP during 1987-92 (Table 3). However, there was a differential pattern of sources of growth in production of selected legumes in different states.

Table 3: Growth rates in production (P), area (A), and yield (Y) of principal legumes in the Indian states of the Indo-Gangetic Plain, 1987-1992.

	Growth rates (% per year)				
Crop/Description	Bihar	Haryana	Punjab	Uttar Pradesh	West Bengal
Black gram					
P	-2.16	-9.04	-15.55	9.01	7.51
A	-3.13	-10.48	-8.16	3.08	4.79
Y	0.99	1.61	-8.05	5.75	2.58
Chickpea					
P	-2.74	11.39	-16.77	-0.74	-14.45
A	-5.68	3.68	19.64	-6.03	-19.86
Y	3.11	7,14	3.56	2.43	6.75
Mung bean					
P	6.17	21.80	9.03	-2.13	-12.02
A	1.78	18.75	4.11	-6.11	-10.45
Y	4.31	2.59	4.73	4.23	-1.76
Groundnut					
P	-2.15	-7.99	-14.52	7.80	3.11
A	-2.84	-14.96	-18.04	0.93	2.03
Y	0.70	8.20	4.29	6.81	1.05
Lentil					
P	3.19	0.12	-10.74	6.57	-10.01
A	0.77	-3.60	-10.01	4.94	-7.94
Y	2.39	3.86	-0.81	1.54	-2.25
Peas and beans					
P	-3.15	4.63	-0.64	10.69	-13.81
A	-0.41	-9.53	3.58	8.46	-23.68
Y	-2.75	15.65	-4.08	2.05	12.93
Pigeonpea					
P	-2.11	9.71	-15.13	-1.86	-11.91
A	-1.99	6.31	-18.89	0.94	-5.75
Y	-0.12	3.18	4.64	-2.77	-6.53
Soybean					
P	NA[1]	NA	NA	10.79	NA
A	NA	NA	NA	3.01	NA
Y	NA	NA	NA	7.54	NA

[1]NA indicates growth rates were not computed as the area under the crop was negligible.

Source: Directorate of Economics and Statistics, Government of India: computed from the data collected from various issues of the Agricultural Situation in India.

In Punjab, only mung bean showed an increase in production. Both area expansion and yield increase were responsible for enhanced production of mung bean. This crop is largely grown as a catch crop during summer after the harvest of wheat. It is likely that it will continue to be the major grain legume in Punjab. Increasing production trends were apparent for mung bean and lentil in Bihar; and for black gram and groundnut in West Bengal. While yield increase was the main source of growth in production of mung bean and lentil in Bihar, rapid area expansion of black gram and groundnut was largely responsible for increased production in West Bengal. In Uttar Pradesh, the main source of increased production was, enhanced yields of black gram and groundnut, and area expansion in lentil, peas and beans. In Haryana, area increase was responsible for high production of mung bean and pigeonpea, while yields of chickpea, peas and beans contributed to high production. It is likely that area under pigeonpea, chickpea, and mung bean will further increase in the state due to the availability of high-yielding, disease-resistant and short-duration varieties of these crops.

LEGUMES AND N FERTILIZER CONSUMPTION

Beneficial residual effects of legumes have been attributed to sustaining fertility status of the soils, and saving inorganic fertilizer in subsequent non-legume crops (particularly N fertilizer). An analysis was, therefore, undertaken to examine relationships between area under legumes and consumption of N fertilizers. Although there are several factors determining consumption of N fertilizers, grain legumes also play a significant role in deciding fertilizer consumption due to their inherent characteristics of residual effects. Cross-district analysis (three years average ending 1992/93) revealed that districts allocating high area under grain legumes consumed low levels of N fertilizer (Table 4). Districts occupying >20% area under grain legumes consumed only 28.2 kg N ha^{-1} while districts covering <5% area under grain legumes applied 88.2 kg N ha^{-1}. Obviously, two reasons explain this phenomenon. First, legumes require less fertilizers. More area

Table 4: Grain legume area and fertilizer consumption in districts of Haryana, Punjab, and Uttar Pradesh states of India.

Legume area (%)[1]	Average annual fertilizer consumption[1] (kg N ha^{-1})	Percentage of distics showing indicated growth in rice yields[2]		
		<2.5%	2.5-5%	>5%
<5	88.2	42	13	45
>5-10	68.3	12	28	60
>10-20	58.9	20	40	40
>20	28.2	0	80	20

[1] Average of data of three years from 1990/91 to 1992/93.

[2] During 1987 to 1992.

Source: Computed from the data collected from the Fertiliser Statistics of India.

under legumes means less fertilizer consumption. Second, legumes fix atmospheric N and improve soil fertility. Their residual effect saves use of inorganic fertilizers in the subsequent crop.

It may be argued that low N fertilizer consumption could adversely affect growth in yields of rice and wheat. Therefore, districts were classified according to intensity of legumes and growth rates in rice and wheat yields. It is interesting to note that all the districts growing grain legumes in more than 20% area achieved annual growth in rice yield of more than 2.5% (Table 4). On the other hand, only 58% districts growing grain legumes in <5% of the total area witnessed >2.5% growth in rice yields. These results give some indication that rice yields are sustainable despite low N fertilizer consumption in high intensity grain legume areas.

The growth in wheat yields were not as clear as that in rice yields. It may be because most of the grain legumes are either grown during the postrainy season (e.g., chickpea, lentil, pea, and bean) or summer (e.g., black gram and mung bean), and their residual effect is observed in the subsequent rainy season crop, namely, rice.

CASE STUDIES ON RESIDUAL EFFECTS OF LEGUMES ON RICE

Farmers in the Terai region of Nepal were interviewed through the Rapid Rural Appraisal (RRA) approach to understand their perception on residual effect of legumes on subsequent cereal crops (Pande and Joshi 1995). The RRA is a technique to understand the problems and opportunities of farming through group discussions with the farmers (Chambers 1992). This approach was used to obtain farmers' perceptions on the residual effect of legumes on subsequent crops. These results are not based on the actual monitoring of soil analysis and experimentation. It is therefore suggested that before embarking on any policy decisions or launching any activity, field experiments on the residual effects of different legumes in different agroecological zones are necessary. Farmers' response in 11 districts of Nepal revealed that legumes, in comparison to wheat or fallow land, contributed to enhanced yields of rice ranging between 10% and 40% (Table 5). In an experiment conducted during 1994-95 in the Kathmandu Valley, various legumes increased the yield (grain at 12% moisture) of the succeeding rice crop by 20-40%, in comparison to yield following wheat (Pandey et al. 1998). These results are in the neighborhood of farmers' perceptions on the beneficial effect of legumes on the subsequent cereal crop.

A study was conducted in High Barind Tract of Bangladesh to assess the cost of cultivation in a subsequent rice crop under two options: (1) preceding chickpea, and (2) fallow land (Islam et al. 1996). The results showed that there was a net saving in cost of fertilizer (about 47%) applied to the rice crop if chickpea was included in the rotation, as against keeping the land fallow. The profitability of the subsequent rice crop was about 13% higher when it was rotated with chickpea.

Table 5: Farmers' perceptions on residual effects of legumes on the yield of subsequent crops in the Terai region of Nepal during 1995.

District	Legume	Subsequent crop	Yield increase (%)[1]
Morang	Khesari	Rice	20
	Lentil	Rice	10-15
Sunsari	Lentil	Rice	15-20
	Black gram	Rice	15-20
Sirah	Chickpea	Rice	25
Dhanusha	Lentil	Rice	40
Mohatari	Lentil	Rice	10-15
Sarlahi	Lentil	Maize	50
Rauthaut	Lentil	Rice	20
Rupandeyhi	Lentil	Rice	15
Kapilvastu	Lentil	Rice	25
Banke	Lentil	Rice	20-25
	Chickpea	Rice	35
Bardia	Chickpea	Rice	25

[1] Estimation is qualitative and based on farmers' perceptions; increase in yield of crop after legume compared to that after fallow/wheat.

Source: Pande and Joshi (1995).

These studies revealed that legumes contribute significantly in enhancing yields of subsequent crops and saving inorganic fertilizers. Despite their importance in improving the sustainability of crop cultivation in IGP, there is a large-scale shift in the cropping pattern in favor of rice-wheat due to relative profitability, availability of better technology, and assured input and output markets (Malik 1994). A technological breakthrough in legumes is required which substantially increases yields, minimizes risk, and enhances profitability.

CONCLUSIONS

Grain legumes in the IGP are generally less preferred by the farmers. However, there are wide spatial differences in choice and extent of legumes in the IGP. Despite increases in yields of some important legumes, decline in area during the past two decades has adversely affected their production. It is expected that area under several legumes may increase due to availability of improved cultivars and high output prices.

Legumes also contribute in saving N fertilizers and thus a decline in cost of production. Farmers' perceptions revealed that inclusion of legumes in cereal-based cropping systems increased the yield of subsequent cereal crops, but more quantitative data is needed for the major crop rotations. Development of appropriate legume technologies, their effective demonstration, and seed sector support may encourage farmers in the IGP to grow legumes to increase their income and improve the soil fertility status, and thus enhance the sustainability of the rice-wheat based system.

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2

Biological Nitrogen Fixation and Residual Effects of Winter Grain Legumes in Rice and Wheat Cropping Systems of the Indo-Gangetic Plain

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ABSTRACT

Legumes have long been recognized by farmers and scientists alike as builders and restorers of soil fertility. Chickpea, the dominant winter legume in India and Pakistan can potentially fix at least 80% of its nitrogen (N) needs from air (like other legumes) and can acquire up to about 140 kg N ha^{-1} from air. Lentil, a major winter legume in Nepal and Bangladesh can potentially acquire about 190 kg N ha^{-1} from air. But the quantities of N_2-fixation by these legumes in farmers' fields in these countries are normally much less than half the potential fixation levels, according to experiments using ^{15}N methods. An increase in irrigation facilities, ready and cheap availability of chemical fertilizers, relatively less stable yields of legumes, and government policies favoring cereal production have driven away the legumes from the intensive cropping systems of the Indo-Gangetic Plain. Any significant increase in area under winter legumes in the intensive cereal-cereal cropping system will require a change in this scenario.

Also, it seems that the continuous cereal-cereal cropping system has changed the soil environment (including high mineral N levels suppressive to N_2 fixation by legumes) such that it is less conducive for producing high yields of legumes. This needs to be confirmed. It is possible to develop cultivars of winter legumes suitable for the likely new soil environment (such as increased mineral-N). Chemical fertilizers were regarded as important inputs for yield increases of

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cereals during 1960s to 1980s. Since then yields have plateaued and even declined, but use of chemical fertilizers (and other agrochemicals such as pesticides) is still growing significantly. Soil organic matter, an important pool of nutrients for raising crops, is feared to have declined significantly. Frequent application of organic materials such as farm-yard manure should help maintain soil organic matter and may ameliorate the suppressive effect of soil mineral-N on N_2 fixation by winter legumes. This aspect needs to be studied.

The Indo-Gangetic Plain (IGP) constitutes a major assured irrigated area and rice *(Oryza sativa)-wheat (Triticum aestivum)* is its major cropping system. Crop productivity in this ecoregion is plateauing or declining (CIMMYT 1990,1991,1992). But increasing human population (nearly 2% per annum) demands increased production of these staple grains. This means that major cropping systems of the region need critical evaluation to devise strategies to increase or to sustain their productivity.

The importance of legumes as builders and restorers of soil fertility has long been recognized. Productivity of soils of the region was perhaps maintained over the years as legumes were regularly grown in the past. Apart from their recognized positive effects on soil fertility, grain legumes are important ingredients of diets of the people in the region and legume fodders are important for livestock. However, the need to grow more food for the increasing population, significant increase in irrigation facilities, ready and cheap availability of nitrogenous fertilizers, and market forces have significantly reduced the area under legumes in the IGP (Joshi 1998; Kumar Rao and Rupela 1998). This paper addresses our current understanding on nitrogen (N) fixation by winter legumes and their residual effect with particular reference to rice- and wheat-based cropping systems of the IGP. Research information specific for the IGP region, however, is very scanty. All available information from unpublished reports and from reports with limited circulation have been used. Data from non-IGP areas have only been used to provide an overall perspective on the topic.

Much of the work on N_2 fixation by legumes in the IGP involved development and evaluation of rhizobial inoculants. The inoculation technology has been adopted in farmers' fields and therefore data on N_2 fixation from on-farm experiments only have been used in this paper. Some legumes, particularly chickpea *(Cicer arietinum),* are best suited to dry areas. With the increase in irrigation facilities and use of chemical fertilizers the microclimate, particularly that of soils, in the IGP seems very different than a legume would face in climatically drier areas. Possibilities to harness biological nitrogen fixation (BNF) by legumes in these changed environments is discussed.

BIOLOGICAL NITROGEN FIXATION BY WINTER GRAIN LEGUMES

With the increase in irrigation facilities and ready availability of fertilizers in the IGP, area under legumes has greatly reduced in the past 2-3 decades. Farmers are aware of the importance of legumes in cropping systems (Joshi 1998). But they seem to have other alternatives to the good value of legumes (source of fixed N_2 and as a break crop) particularly in the intensively cultivated areas of the IGP. Chemical fertilizers can provide N and other high value crops, such as sunflower *(Helianthus annuus),* can break the continuous rice-wheat cycle. In addition, with continuous rice-wheat the soil environment seems to have become less conducive for N_2 fixation by legumes, particularly for chickpea. High soil mineral N is known to suppress BNF by legumes (Streeter 1988; Rupela and Johansen 1995). Soils in at least some parts of the IGP already have suppressive levels of soil mineral N (Kumar Rao and Rupela 1998).

A survey of the literature revealed that much of the work on BNF by winter grain legumes in the four IGP countries (Bangladesh, India, Nepal, and Pakistan) was on evaluation and development of rhizobial inoculants. A large number of experiments on response to rhizobial application have been published from the region based on the work done at research stations (Khurana and Dudeja 1981; Podder and Habibullah 1982; Rewari 1985; Bhattarai and Shrestha 1989; Namdeo et.al. 1989). Lately, the rhizobial application technology has been transferred to farmers' fields as part of the coordinated research programs [such as that coordinated by the International Atomic Energy Agency (IAEA), Austria] within and between countries. Almost all the experiments conducted at a large number of sites suggested a positive yield response due to rhizobial application. Data compiled from three papers presented at a workshop on BNF at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, 20-24 August 1996, suggested 19-63% improvement in chickpea yield and 11-32% improvement in lentil (*Lens culinaris)* yield in farmers' fields (Table 1).

Table 1: Response to rhizobial inoculation of chickpea and lentil cultivars in farmers' fields during 1993/94 to 1995/96.

Legume/ Country	No. of locations	Yield (t ha^{-1}) of noninoculated plots		Mean increase due to rhizobial inoculation over control (%)	Reference
		Range	Mean		
Chickpea					
Bangladesh	211	0.62-1.45	1.01	35.9	Sattar et al. (1997)
India	50	0.64-1.75	1.08	18.5	Khurana et al. (1997)
Pakistan	20	0.20-0.50	0.25	63.2	M. Aslam, NARC, Pakistan (personal communication)
Lentil					
Bangladesh	203	0.54-1.20	0.84	28.8	Sattar et al. (1997)
India	14	0.41-1.06	0.79	11.4	Khurana et al. (1997)
Nepal	13	0.70-1.70	0.95	32.3	Bhattarai et al. (1997)

[1]A11 the experiments on farmers' fields (except those conducted by the Bangladesh Agricultural Research Institute) were non-replicated. Plot size was generally 24 m^2 in Bangladesh, and 0.42 ha in India. In Nepal a plot size of 100 nr was intended but actual plot size varied depending upon the availability of land with a farmer.

Both chickpea and lentil are traditional legumes in the region and such large responses to rhizobial inoculation were unexpected. Rhizobial inoculation also resulted in increased N_2 fixation from air (measured by ^{15}N methods) in the experiments in Bangladesh and Pakistan conducted under the auspices of the IAEA (Table 2). Although the per cent N derived from air (%Ndfa) in the inoculated chickpea in Bangladesh (70-81%) was slightly more than that of the uninoculated chickpea (54-74%), the inoculated chickpea acquired substantially more N (83 kg N ha^{-1}) than that by the control (42 kg N ha^{-1}). Similarly, inoculated lentil in Pakistan acquired 14 kg N ha^{-1} more than N acquired by uninoculated lentil (7 kg N ha^{-1}).

Table 2: Grain yield and nitrogen (N) fixed and removed from soil (^{15}N enrichment method) as affected by rhizobial inoculation of chickpea in Bangladesh and lentil in Pakistan.

	Noninoculated control		Rhizobial inoculation	
Character	Range	Mean	Range	Mean
Chickpea (Bangladesh)				
Grain yield (t ha^{-1})	0.59-0.67	0.64	0.78-0.95	0.86
Total N yield (kg ha^{-1})	58-75	68	102-126	111
%Ndfa[1]	54-74	63	70-81	76
Amount of N (kg ha^{-1})				
from fixation	34-49	42	80-87	83
from fertilizer	2.5-4.3	3.5	3.0-5.6	4
from soil	15-26	21	17-33	23
Lentil (Pakistan)				
Grain yield (t ha^{-1})	NA[2]	0.31	0.42-0.48	0.44
Total N yield (kg ha^{-1})	NA	38	52-67	60
%Ndfa	NA	19	26-33	30
Amount of N (kg ha^{-1})				
from fixation	NA	7	15-24	21

[1] Percent nitrogen derived from air.

[2] NA = Data not available

Source: Sattar et al. (1998); Hafeez et al. (1998).

Experimental estimates (most of them from non-IGP locations, countries) of N_2 fixation by the winter legumes [chickpea, lentil, pea *(Pisum sativum)* and faba bean *(Vicia faba)]* are given in Table 3. In most experiments at least 50% of the N in the legumes was derived from air. The potential N_2 fixation was maximum in faba bean (330 kg N ha^{-1}) followed by pea (244 kg N ha^{-1}), lentil (192 kg N ha^{-1}), and chickpea (141 kg N ha^{-1}). Quantities of N_2 fixed varied greatly in each of the four legumes (Table 3). Reasons of such a variation have been discussed by Kumar Rao and Rupela (1998). Estimates of N_2 fixation in chickpea (measured by the difference method using nonnodulating chickpea line as a reference) ranged from 0 to 54 kg N ha^{-1} in India (Table 4). For 20 chickpea cultivars assessed in Pakistan using the ^{15}N dilution method, with wheat as a reference, N_2 fixation ranged from 4 kg N ha^{-1} to 61 kg N ha^{-1}. It has been observed in several studies that total

Table 3: Range of experimental estimates of the proportion (%Ndfa) and amount of nitrogen (N) fixed by some winter legumes[1].

Legume	%Ndfa	Amount N_2 fixed (kg N ha^{-1})
Chickpea *(Cicer arietinum)*	8-82	3-141
Lentil (*Lens culinaris)*	39-87	10-192
Pea *(Pisum sativum)*	23-73	17-244
Faba bean *(Viciafaba)*	64-92	53-330

[1]Data mainly from non-Indo-Gangetic Plain countries.
Source: Peoples et al. (1995).

Table 4: Experimental estimates of nitrogen (N) fixed by chickpea in Bangladesh, India, and Pakistan.

Location	N_2 fixed (kg ha^{-1})[1] Range	Mean	Comments
India[2]			
Akola (1994/95)	11-54	29	Experiment involved six cultivars of different nodulation capacities, at least 3 replications, plot size 12 m^2 and non-nodulating chickpea was used as reference (Dudeja et al. 1997).
Akola (1995/96)	21-40	32	The six cultivars as above were grown at two different soil-N levels, at least 3 replications, plot size 12 m^2, and, non-nodulating chickpea was used as reference (Dudeja et al. 1997).
Badnapur (1995/96)	0-18	7	The six cultivars as above were grown at two different soil-N levels, at least 3 replications, plot size 12 m^2, and, non-nodulating chickpea was used as reference (Dudeja et al. 1997).
Sehore (1994/95)	9-33	24	The six cultivars as above were grown at two different soil-N levels, at least 3 replications, plot size 12 m^2, and, non-nodulating chickpea was used as reference (Dudeja et al. 1997).
Bangladesh[3]	61-126 (81 -88)	86 (86)	Eleven cultivars evaluated at Bangladesh Institute of Nuclear Agriculture, Mymensingh, post-rainy season 1993/94 (Sattar et al. 1998).
Pakistan[4]	4-61 (23-68)	22 (44)	Twenty cultivars evaluated (2.7 m^2 plots, 3 replications) at the Nuclear Institute of Agriculture and Biology, Faisalabad, post-rainy season 1993/94 (Hafeez et al. 1998).

[1]Data in parentheses are percent N derived from fixation (%Ndfa).
[2]Fixed N only in grains was assessed
[3]Amount of N_2 fixed is in mg N $plant^{-1}$. Wheat *(Triticum aestivum)* was used as a reference crop in Bangladesh.
[4]Wheat and barley *(Hordeum vulgare)* were used as reference crops in Pakistan.

biomass and grain yield correlate well with %Ndfa and can be used for screening genotypes (Herridge et al. 1994). Thus by selection for high yield in a soil with low levels of mineral N one would most likely be selecting for high N_2 fixation.

Some studies have reported levels of N_2 fixed by winter legumes in farmers' fields in IGP countries. A large range of %Ndfa (measured by the ^{15}N natural abundance method) has been measured in chickpea (65-87% in Nepal, 21-88% in 1994/95 in Pakistan, 41-95% in 1995/96 in Pakistan), lentil (64-93% in Nepal, 55-91% in Pakistan), and khesari *(Lathyrus sativus)* (85-91% in Nepal), (Table 5) (Aslam et al. 1997; Maskey et al. 1997; Shah et al. 1997). These legumes were rainfed crops from regions that grew wheat. Year to year variation in quantities of N_2 fixed by chickpea in the same region (40-44 fields surveyed in each year) seemed related to rainfall in the preceding rainy season.

Table 5: Estimates of nitrogen (N) fixed (^{15}N natural abundance method[1]) by winter legumes in farmers' fields in Nepal and Pakistan.

Legume	No. of fields	%Ndfa Range	%Ndfa Mean	Amount (kg N ha^{-1})[2] Range	Amount (kg N ha^{-1})[2] Mean	References
Nepal (1995/96)						
Chickpea	9	65-87	79	35-80	56	Maskey et al. (1997)
Lentil	10	64-93	78	19-83	50	Maskey et al. (1997)
Khesari	4	85-91	88	NA	NA	Maskey et al. (1997)
Pakistan						
Lentil (1993/94)	40	55-91	78	16-83	47	Shah et al. (1997)
Chickpea (1994/95)	44	21-88	*75*	<20-78	38	Aslam et al. (1997)
Chickpea (1995/96)	42	41-95	81	21-91	74	Aslam et al. (1997)

1 Combinations of local weeds in the observation plots of wheat and mustard were used as reference species. $\delta^{15}N$ value of -1.65 for chickpea and -1.50 for lentil was used for the legumes fully dependant on N_2 fixation.

2 Data on amount of N_2 fixed by chickpea and lentil in Nepal was obtained from S.L. Maskey, NARC, Nepal; NA = data not available.

Rhizobial inoculation of winter legumes can contribute significantly to the N economy (31-53 kg N ha^{-1} in chickpea, and up to 14 kg N ha^{-1} in lentil) of relevant cropping systems (Table 2). By using high-yielding and high N_2-fixing cultivars, and by exploiting an understanding of factors that affect BNF (Kumar Rao and Rupela 1998), the quantity of BNF can be further enhanced.

RESIDUAL EFFECTS OF WINTER LEGUMES

Discussion with farmers in the IGP region revealed that they are well aware of the beneficial effects of legumes (Joshi 1998). Improved yield of crops following legumes has been widely observed by farmers and recorded by researchers. This may be due to N_2 fixation by legumes, breaking cycles of pests and diseases, improvements in soil microbial, chemical, and physical characteristics, and increased activity of soil macrofauna e.g., earthworms (Peoples and Craswell 1992; Kundu and Ladha 1995; Wani et al. 1995). But in most cases rotational benefits of annual crop legumes can be attributed to an improvement in the N economy of soils measured by improved soil reserves of readily mineralizable organic N and microbial biomass carbon and nitrogen (Dalai et al. 1994; Rupela et al. 1995; Wani et al. 1995). An increase in plant available N (nitrate) in soil due to legumes has been measured. Additional soil nitrate after chickpea (14 kg N ha^{-1}) and pea (28-38 kg N ha^{-1}) than after wheat to a depth of 60 or 120 cm has been reported (Jensen and Haahr 1990; Herridge et al. 1995). This extra nitrate, detectable even during growth of the legume, can result from a reduced use of soil nitrate already present in the soil (Evans et al. 1991; Herridge et al. 1995), which is termed as the "nitrate-sparing" effect of legumes. The combination of conserved soil-N, greater mineralization potential of soil-N, and return of the fixed N_2 from fallen leaves and underground plant parts (above-ground plant parts other than grains are also removed by farmers in the region because of their economic value as fodder) has been assessed in some agronomic studies in India. Many of these studies have not been formally published but were available in reports with limited circulation.

The %Ndfa of different winter legumes ranged from 8% to 95% (Tables 3,4, and 5). This means that even under the most conducive N_2 fixation conditions a legume derives part of its N from the soil mineral N pool. Where most or all the above-ground plant parts of a legume are removed from the field, as is mostly the case in the IGP, it is most likely that there will be a net loss of N from soil (negative N balance) unless replenished by fertilizer N. In a field study at Gwalior in northern India a negative net N balance that ranged from - 64 kg ha^{-1} to - 77 kg ha^{-1} was measured in six chickpea cultivars (Wani et al. 1995). These cultivars fixed only 26-10 kg N ha^{-1}. The net N balance measured for pea in farmers' fields in Australia, where crop residues were returned to soil, ranged from -2 to +21 kg ha^{-1} (Peoples et al. 1995).

In spite of a negative N balance, yield of subsequent crops after legumes is invariably greater than that after cereals for the reasons indicated above and discussed by Kumar Rao and Rupela (1998). Terms such as "N residual effect (De et al. 1983)" and "fertilizer N replacement value" or "N equivalent" (Hesterman et al. 1987) are used to describe the role of legumes in crop rotations. These refer to the amount of inorganic N required following a non-legume crop to produce another non-legume crop with an equivalent yield to that obtained following a legume. This comparison provides a quantitative estimate of the benefit of the legume, in terms of fertilizer N, on the following non-legume crop (Table 6). The concept of fertilizer N equivalent does not distinguish between BNF and the "N-sparing" effect which results from substitution by the legume of biologically fixed N_2 for soil N. Fertilizer N equivalent methodology has been widely used but it overestimates the

Table 6: Residual effect of preceding legume on cereal yield in terms of fertilizer nitrogen (N) equivalent.

Preceding legume	Following cereal	Fertilizer N equivalent (kg ha^{-1})
Chickpea	Maize	60-70
Chickpea	Pearl millet	40
Lentil	Maize	18-30
Lentil	Pearl millet	40
Pea	Maize	20-32
Pea	Pearl millet	40
Khesari	Maize	36-48

Source: Derived from Ahlawat et al. (1981), Chandra and Ali (1986), De and Gautam (1987), Nambiar et al. (1988) and Roy Sharma and Singh (1969).

BNF contribution of a legume in a crop rotation. Also, it gives variable estimates depending on the test crop (Peoples et al. 1995). Field studies at the Indian Agricultural Research Institute (IARI), New Delhi, India have clearly revealed that different grain legumes increased grain yield of succeeding maize, on an average, by 19% when compared with fallow and 29% when compared with wheat. Chickpea was more efficient in increasing the grain yield of maize *(Zea mays)* as compared to pea, lentil, or khesari. The N uptake by maize was maximum after chickpea (94 kg ha^{-1}) and minimum after wheat (63 kg ha^{-1}) (Fig. 1).

Field studies by Patel et al. (1981) involving post-rainy season grain legumes in a cropping sequence at IARI, revealed that inclusion of post-rainy season grain legumes (chickpea, lentil, khesari, and pea) improved the soil fertility status by increasing the organic matter, and available N and phosphorus (P). The succeeding crop benefited from the preceding legumes. Total annual production was almost double and the production potential in terms of maize grain equivalent was 3-4 times more from a legume-maize sequence than from a wheat-maize sequence. From an economic point of view, maize grain equivalent and net returns obtained were highest with preceding chickpea followed by lentil, wheat, pea, or khesari, and were least after fallow. Post-rainy season grain legumes benefited following maize to the extent of 50-60 kg N ha^{-1} for a targeted yield of 4 t ha^{-1} of maize grain.

Different legumes have the capacity to leave behind different amounts of N for use by the succeeding crops. It has been estimated that 0.668 million t of N can be incorporated in the soil through the inclusion of legumes in cropping systems (Saraf et al. 1990). Inclusion of legumes in cropping systems has been found to contribute around 50 to 60 kg N ha^{-1}. The amount of N contributed by the legume for the succeeding cereal was 60 kg ha^{-1} in chickpea, and 50 kg ha^{-1} in khesari. Pulse crops can be made more effective by rhizobial inoculation (Tables 1 and 2). Thus in situations where consumption of fertilizers is very low, the residual fertility build-up through legumes is possible (Hegde and Dwivedi 1993). In another study, post-rainy

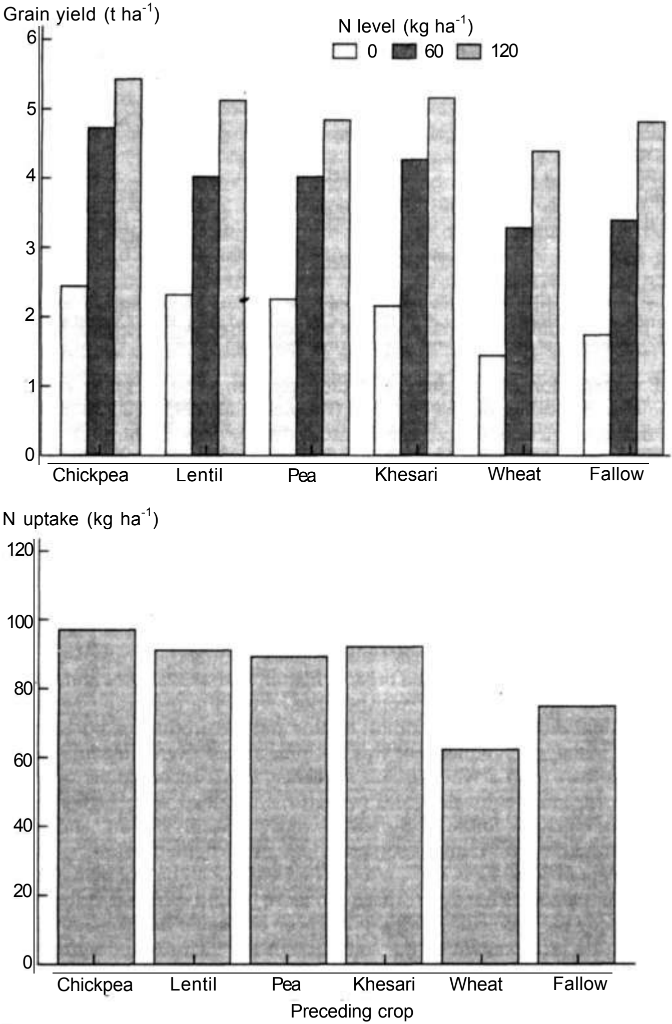

Figure 1: Grain yield and nitrogen (N) uptake of maize as affected by preceding crop and fertilizer N levels at the Indian Agricultural Research Institute, New Delhi, India *(Source:* Saraf and De, unpublished).

season legumes substituted 25% of the fertilizer N needs of rice and pearl millet *(Pennisetum glaucum)* (Hegde 1992). Studies carried out at several locations for many years in the All India Coordinated Agronomy Research Project (AICARP) have indicated that introduction of legumes to replace one of the crops in a rice-wheat cropping system had substantial residual effects on the succeeding crop of rice or wheat, and increased net returns (Table 7).

Table 7: Productivity and profit from rice-wheat and rice-legume or legume-wheat cropping systems at different locations in India

Location/ Cropping system	Average productivity (kg ha^{-1})[1] *Kharif*	*Rabi*	Net returns (Rs ha^{-1})[2]
Pantnagar			
Rice-wheat	3945	4207	11218
Rice-lentil	4299	1506	14445
Varanasi			
Rice-wheat	3648	3419	8727
Rice-chickpea	3838	1407	11770
Kanpur			
Rice-wheat	3614	3560	9095
Rice-chickpea	3797	1803	13815
Black gram-Wheat	1330	3855	11861
Ludhiana			
Rice-wheat	6111	4372	17271
Rice-pea	6481	2064	22955

[1] *Kharif* = rainy season; *Rabi* = post-rainy season.

[2] 1 US$ = Rs. 39.70 in April 1998.

Source: Hedge (1992).

In Bangladesh, Patwary et al. (1989) observed that the total grain and straw yield of rice increased by about 12% following chickpea and 8.5% following lentil in relation to rice following wheat (Table 8). The total N uptake in rice grain following grain legumes (36.8 kg ha^{-1} following chick-pea and 36.4 kg ha^{-1} following lentil) was substantially higher than the N uptake following a wheat crop (28.8 kg ha^{-1}). The total N yield of rice following legumes was also higher than that following cereal (Table 8).

Table 8: Yield and total nitrogen (N) uptake in rice as affected by preceding wheat or legumes in Bangladesh.

	Total yield (t ha^{-1})		N uptake (kg ha^{-1})		
Preceding crop	Grain	Straw	Grain	Straw	Total
Chickpea	5.27	3.47	36.8	12.6	49.4
Lentil	5.10	336	36.4	13.4	49.8
Wheat	4.72	3.08	28.8	11.2	40.0

Source: Patwary et al. (1989).

In an experiment conducted at IARI, the beneficial effects of preceding legumes were more pronounced in maize receiving no fertilizer. The legume carry-over effect was attributed to higher N and P status of the soil after legumes that reflected favorably on the productivity of succeeding maize and its attributes. Mean "N-equivalent" value of the four legumes (chickpea, pea, lentil, and khesari) was 131 kg N over wheat and *67* kg N over fallow (Table 9).

Table 9: Nitrogen (N) economy of preceding winter legumes on maize at the Indian Agricultural Research Institute, New Delhi, India.

Description	Khesari	Chickpea	Pea	Lentil	Fallow	Wheat
A: Maize grain yields (kg ha^{-1}) produced from the plot of preceding legumes over wheat and fallow under no N.						
Over wheat	1773	1375	1150	1299	789	-
Over fallow	984	566	366	510	-	789
B: Fertilizer N requirement (kg ha^{-1}) to match legume effect.						
Over wheat	164	126	110	123	70	
Over fallow	116	69	32	52	-	70

Source: Patel et al. (1981).

EFFECT OF LEGUMES ON SOIL PROPERTIES

The nature of crop, cropping system, tillage, and other management practices followed for raising crop(s) exert differential influences on soil properties. Legumes are beneficial in cropping systems/rotations for N economy and as cover crops for checking soil erosion, thus contributing to the cropping system, soil fertility and productivity. The build-up of organic matter leading to improvement of soil structure by legumes, especially with the application of phosphate to the legumes, has been reported by some researchers (Morey 1976; Padma Raju 1967).

Properties such as soil pH, electrical conductivity, and texture are not influenced much by legumes (Padma Raju 1967). Legumes in a cropping system, however, improved the physical properties of soil. Improvement in soil structure due to inclusion of chickpea and other legumes has been measured by Shende and Sen (1958), Biswas et al. (1970), and Morey (1976). Legumes can lower the bulk density of soil (Prabhakara 1970; Morey 1976). Padma Raju (1967) reported better soil aggregation due to inclusion of legumes in cropping systems. Morey (1976) studied soil aggregation in a long-term rotational experiment and reported higher percentage of soil aggregates exceeding 0.25 mm in a cropping system involving legumes.

EFFECT OF WINTER LEGUMES ON SOIL FERTILITY

Organic carbon content increased in legume-based cropping systems as compared to wheat-maize or fallow-maize cropping sequences. Among the legumes, khesari as a preceding crop proved superior to lentil, pea, and chickpea, which in turn significantly increased the organic carbon in soil over fallow and wheat treatments (Table 10). The increase in organic carbon content in soil through legumes has also been reported by Rixon (1966). The build-up of soil organic matter through growing legumes has also been reported by Russell (1977).

Table 10: Fertility status of soil under winter legumes and rainy season maize sequence.

Preceding crop	After harvest of winter crop and before sowing of following maize[1]			After harvest of maize and before sowing of winter legumes		
	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})
Khesari	0.553	166.8	13.8	0.467	142.3	13.4
Lentil	0.454	153.5	13.0	0.421	128.8	12.1
Pea	0.431	143.4	12.5	0.399	119.6	11.6
Chickpea	0.502	161.3	13.6	0.453	140.5	12.0
Fallow	0.389	115.4	11.4	0.365	109.7	10.7
Wheat	0.365	106.4	11.2	0.347	102.0	10.9
LSD at 5%	0.041	11.2	0.8	0.084	8.9	0.8

[1] OC = organic carbon; N = nitrogen; and P = phosphorus.

Source: Ahlawat et al. (1977).

Available N in soil increased when estimated immediately after the harvest of winter legumes and even after the harvest of a succeeding crop of maize in the rainy season (Table 10) (Ahlawat et al. 1977). The plots of preceding legumes possessed higher soil N levels than the fallow and wheat plots. Application of fertilizer N to maize at 60 and 120 kg N ha^{-1} also improved the nitrogen status of soil by 14 and 17 kg N ha^{-1}, respectively, over that with no N fertilization.

Available P in soil for utilization by a succeeding maize crop was higher in plots grown with winter legumes compared with wheat and fallow (Table 10). It was also higher in a legume-maize sequence even after the harvest of the maize crop. The increased availability of P in winter legume plots may be attributed to an effect of organic acids produced by the legume roots. This could also be due to mineralization of organo-phosphatic compounds and solubilization of insoluble soil organic phosphate thereby releasing more P in an available form (Nair et al. 1973).

RESEARCH NEEDS AND STRATEGIES TO HARNESS THE VALUE OF LEGUMES

A total of at least 300 kg nutrients (N, P_2O_5, K_2O) ha^{-1} is recommended for rice-wheat or rice-rice cropping annually. Based on the data of 1995 derived from statistics of the Food and Agriculture Organization of the United

Nations (FAO), Italy, this amount was about twice the average total fertilizer consumption ha^{-1} $annum^{-1}$ in Bangladesh and Pakistan, about threefold of that in India and about eight-fold of that in Nepal. This indicates that rice and wheat receive a major share of the chemical fertilizers in the IGP countries. In some regions of the IGP (such as in Punjab, India) farmers use more than the recommended levels of fertilizers. In a survey conducted in September 1996 it was observed that 56% farmers (of the 231 surveyed farmers cultivating 2383 ha) used more than the recommended level of nitrogen (120 kg ha^{-1} each for rice and wheat) for rice and 5% farmers used more than recommended level for wheat (Sidhu et al. 1998). The reported soil-mineral N levels [mean of 5 to 23 farmers' fields reported in four publications: 61 to 96 mg kg^{-1} soil; see details in Kumar Rao and Rupela (1998)] in Punjab, India are already high enough to significantly suppress BNF (20 to 140 ppm N may suppress N_2 fixation trait(s) approximately by 50% in several legumes; see summary table in Rupela and Johansen (1995) based on published literature). The apparent high use of fertilizer N and consequent high soil mineral N may be one of the reasons for the low level of N_2 fixation (4 to 126 kg ha^{-1}) in farmers' fields in the IGP countries (Tables 4 and 5) compared to the reported high potential levels (141 to 330 kg ha^{-1}) of N_2 fixation (Table 3). Essentially, the soil environment in the rice-rice or rice-wheat cropping system is much different (in terms of N, P, soil moisture, soil compaction, and soil organic matter) than in annual rainfed cropping systems where legumes are largely grown traditionally.

Legumes may be affected by soil-borne diseases in the rice-wheat or rice-rice cropping systems that may be unimportant otherwise. Roots and nodules of chickpea have been found severely affected by black root rot (caused by *Fusarium solani)* in rice-wheat system fields in Bangladesh, Nepal, and Punjab, India (unpublished observations of O P Rupela, ICRISAT, India, during nodulation surveys in these countries). Any program aiming to increase the area under legumes in general and chickpea in particular should consider such adverse factors that may already be affecting yield and stability of these legumes. Studies confirming suitability (or otherwise) of the soil environment for winter legumes, in areas continuously growing rice-wheat or rice-rice will be required. It should be possible to select legume lines able to fix high N at high soil-N levels (Rupela and Johansen 1995). Specific breeding programs targeting particular constraints faced by legumes in rice-wheat cropping systems of the IGP are needed.

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3

Biological Nitrogen Fixation and Residual Effects of Summer and Rainy Season Grain Legumes in Rice and Wheat Cropping Systems of the Indo-Gangetic Plain

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ABSTRACT

Various methods of estimation of biological nitrogen fixation (BNF) are examined for legumes in general, and summer and rainy season legumes of the Indo-Gangetic Plain in particular. The residual effects of summer grain legumes on rice, and rainy season legumes on wheat in double cropping systems, and summer legumes in rice-wheat systems are documented. These grain legumes have been found to affect an economy equivalent to 20-60 kg ha^{-1} fertilizer nitrogen (N). The effects on yield and nutrient uptake of subsequent cereal crops were more pronounced when stover of these legumes, after obtaining the economic product, was incorporated into the soil. The mechanisms of residual effect of these crops through nutrient, i.e., N cycling, physical and biological properties of soil, and incidence of pests and diseases have also been indicated. Several future research directions based on the information available so far have been proposed.

In the Indian states of Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, Madhya Pradesh, and Himachal Pradesh, rice (*Oryza sativa)* occupies 24.8 million ha and wheat *(Triticum aestivum)* 21.1 million ha, accounting for 58% and 84% respectively of the country's total area. Pakistan has 2.3 million ha under rice and 8.4 million ha under wheat. Bangladesh grows 10 million ha of rice and 0.7 million ha of wheat. Nepal has 1.4 million ha under rice and 0.57 million ha under wheat (Pandey et al. 1998). The rice-wheat rotational system covers about 10.5 million ha in India mainly in the aforesaid states (Pandey 1992). In Pakistan this system is most prevalent in Punjab (1.5

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million ha) and Sind (0.3 million ha) provinces and is also adopted to a varying extent in North-West Frontier Province and Baluchistan (Zia et al. 1992). The system occupies about 0.5 million ha each in Nepal and Bangladesh. The rice-wheat system has emerged as the most productive cereal grain producing system with a yield potential of 10-14 t ha^{-1} $year^{-1}$ (IARI 1995). In terms of food and nutritional security, both these crops contribute to the extent of 54% of the world food pool and 70% of the Indian food pool.

Rice and wheat are the largest users of inorganic fertilizers. The rice crop on an average removes about 300 kg ha^{-1} of nitrogen (N), phosphorus (P), and potassium (K) besides 0.2 kg ha^{-1} zinc (Zn), 0.75 kg ha^{-1} iron (Fe) and 3.4 kg ha^{-1} manganese (Mn) (Pillai and Kundu 1993). The wheat crop removes about 390 kg ha^{-1} of N, P, and K along with 0.5 kg ha^{-1} Zn, 1.8 kg ha^{-1} Fe, and 0.5 kg ha^{-1} Mn (Joseph and Prasad 1992). The rice-wheat system therefore accounts for annual removal of more than 650 kg ha^{-1} of N, P, and K and micronutrients in the range of 0.5-1.0 kg ha^{-1} Zn, 2-3 kg ha^{-1} Fe, and 3-3.5 kg ha^{-1} Mn (Narang et al. 1990). The rice- and/or wheat-based cropping systems therefore cause a considerable depletion of soil nutrients and their effect on long-term productivity is threatening. Consequently farmers have to use increased fertilizer doses each year to realize the same yield levels which were obtained with relatively lower amounts of fertilizers in the past (CIMMYT 1990, 1991, 1992).

In order to maximize and sustain crop production on a long-term basis, an integrated nutrient management system providing adequate nutrients to meet crop needs while maintaining soil health needs to be developed.

Among the various nutrients required by the component crops of the system, N is of major practical importance because the N removal by rice- and/or wheat-based cropping systems may often exceed 200 kg ha^{-1}. The beneficial role of legumes in replenishing soil N is well established. However, this capability of legumes varies considerably from crop to crop and for the purpose they are grown.

Mung bean *(Vigna radiata),* black gram *(Vigna mungo),* cowpea *(Vigna unguiculata),* soybean *(Glycine max),* and pigeonpea *(Cajanus cajan)* are the major grain legumes grown during the rainy season and followed by wheat in winter. All these legumes have been found to increase the productivity of succeeding wheat when compared with wheat after a fallow or a cereal. Cowpea, however, proved most beneficial (IARI 1996-97). The grain legumes, namely, pigeonpea, black gram, soybean, and cluster bean *(Cyamopsis tetragonoloba)* may affect an economy equivalent to 33-78 kg N ha^{-1} in succeeding wheat as compared to a preceding sorghum *(Sorghum bicolor)* crop (Singh et al. 1993).

Mung bean is the most common grain legume grown in summer to utilize the gap between winter and rainy season crops. It may give yields ranging between 0.5 t ha^{-1} and 1.0 t ha^{-1} and a contribution of equivalent fertilizer N of 25-40 kg ha^{-1} to the following rice crop (Mahapatra et al. 1974; Ali 1992; IARI 1993-94). Further, incorporation of mung bean residues after picking pods has been found as effective as green manuring with other legumes such as *Sesbania* in increasing the productivity of a rice-wheat system (Hegde 1992). Although the effect of green manuring in rice- and/or wheat-based cropping systems has been well documented (e.g. Chatterjee et al. 1979; Tiwari et al. 1988; Goswami et al. 1988), information on the effect of grain legumes on the sustainability and productivity in these cropping systems is meager. An attempt has been made to collate the information available on residual effects of grain legumes in the Indo-Gangetic Plain (IGP) and suggest future research and development needs.

AREA, PRODUCTION, AND PRODUCTIVITY OF MAJOR SUMMER AND RAINY SEASON GRAIN LEGUMES

In rice- and/or wheat-based cropping systems, summer and rainy season grain legumes such as pigeonpea, mung bean, black gram, and cowpea could be grown. The IGP which comprises of Uttar Pradesh, Bihar, Punjab, Haryana, and West Bengal has 0.66 million ha under pigeonpea with an annual production of 0.68 million t, 0.38 million ha, and 0.23 million t of mung bean, and 0.53 million ha and 0.27 million t of black gram (Table 1). These states together occupy about 18%, 11%, and 15% of the total area in India of pigeonpea, mung bean, and black gram respectively and contribute

Table 1: Area, production, and productivity of summer and rainy season grain legumes in the Indo-Gangetic Plain of India, 1992/93.

State/Crop	Area ('000 ha)	Production ('000 t)	Yield (kg ha^{-1})
Bihar			
Pigeonpea	64.4	71.8	1115
Mung bean	211.2	131.2	621
Black gram	88.9	40.2	460
Haryana			
Pigeonpea	53.1	55.0	1035
Mung bean	10.2	5.4	529
Black gram	2.3	1.1	478
Punjab			
Pigeonpea	10.5	9.3	885
Mung bean	47.5	37.3	785
Black gram	6.7	2.0	298
Uttar Pradesh			
Pigeonpea	528.9	544.1	1028
Mung bean	93.1	44.5	476
Black gram	299.7	140.5	469
West Bengal			
Pigeonpea	4.6	4.4	956
Mung bean	14.3	6.9	482
Black gram	137.0	81.2	593

Source: Directorate of Economics and Statistics, Government of India.

28% of pigeonpea, 13% of mung bean, and 14% black gram of total annual production in India. In terms of productivity, the region is above the national average in pigeonpea (1004 kg ha^{-1}) and mung bean (579 kg ha^{-1}). Uttar Pradesh also has a substantial area under spring/summer mung bean. Similarly, Bihar and West Bengal grow a considerable area under winter mung bean. In West Bengal, winter black gram occupies more than 50% of the total area of the state under this crop.

Cowpea is another potential summer or rainy season grain legume for the sustainability of rice and wheat cropping systems. This crop is grown for grain, green pods (vegetable), or fodder during both summer and rainy season. In India, separate production statistics for cowpea are not available. However, it contributes substantially to the soil fertility of various cereal-based cropping systems in the IGP (IARI 1980) besides providing about 5% share in total grain legume production.

BIOLOGICAL NITROGEN FIXATION (BNF)

Legumes can fix atmospheric N to meet their own N needs and also to benefit the succeeding cereal crop. There is comparatively little quantitative information on the amount of fixed N_2 available to crops following legumes in a cropping system. In grain legumes, usually the above-ground plant parts are harvested and removed and therefore the residual effect must largely be derived from the underground plant biomass and the leaf fall during crop growth. In most of the field experiments conducted, the residual effect of legumes is assessed through an increase in yield of a succeeding non-legume. This approach includes applying graded levels of N to a succeeding cereal crop. The residual effect is then expressed in terms of fertilizer N equivalent units required to match the beneficial effect of the legume.

The residual effect of legumes does not necessarily reflect the direct contribution of fixed N_2 but could simply be due to sparing effect of soil N. Maize *(Zea mays)* grown after mung bean, groundnut *(Arachis hypogaea),* and soybean was reported to remove 17-23 kg N ha^{-1} more than maize following maize; however, only in the case of soybean could some of the N uptake be directly attributed to fixed N_2 (Suwanarit et al. 1986). Kumar Rao et al. (1987) adopted a different approach whereby soil was uniformly labeled with ^{15}N and dilution of the enrichment of available soil N by addition of fixed N_2 in plant residues from pigeonpea was examined on the following maize crop. The results showed that decomposing roots and the leaf fall were the source of supply of N (35% of the N in maize came from N_2 fixed by pigeonpea) to the following maize crop.

Methods Used for Estimation of BNF

An accurate measurement of the quantity of N_2 fixed is a prerequisite for any program aimed at enhancing symbiotic N_2-fixation. There are several methods available, each with some advantages and disadvantages. However, the most suitable method to adopt would depend on the objective of the experiment.

The simplest method of quantifying the amount of N_2 fixed over a period of time is the N-difference method. In this method, legumes and reference crops are assumed to absorb similar amounts of N from soil. Erroneous estimates of N_2-fixation may result if this is not the case (Peoples et al. 1989). Kumar Rao et al. (1996b) reported that the N-difference method tended to underestimate the %Ndfa (percentage of nitrogen derived from atmosphere) of extra-short-duration and short-duration pigeonpea compared with the ^{15}N-natural abundance method. However, with medium-duration pigeonpea, which is generally intercropped with cereals such as sorghum or millet but was grown as a sole crop in this case, the N-difference and ^{15}N-natural abundance methods gave similar values of %Ndfa.

Although acetylene reduction assay (ARA) is a simple method, it provides only point measurements of nitrogenase activity which must be integrated for the duration of crop growth (Peoples et al. 1989). The xylem solute technique can be used to assess N_2-fixation indirectly in only those legumes (e.g., pigeonpea) which transport their fixed N_2 in the form of ureides, allantoin, and allantoic acid (Peoples et al. 1989).

The use of ^{15}N enriched gas in which N_2-fixing systems are incubated provides direct evidence for N_2-fixation. This method provides immediate results but there might be errors in extrapolating data from short-term observations to the entire growing season (Knowles 1980). The method is cumbersome and expensive.

The ^{15}N enriched fertilizer-isotope dilution method (ID) is based on differential dilution in the plant of ^{15}N labeled fertilizer by soil and fixed N_2 (Fried and Middelboe 1977). The isotope dilution method and the A-value method are two main variations of this isotope method. The ^{15}N isotope dilution method has been extensively employed both for greenhouse and field studies. In this method equal amounts and enrichments of ^{15}N labeled fertilizer are applied to both fixing and non-fixing reference crops at the time of planting. In the A-value method, different rates of N fertilizer are applied to fixing and non-fixing plants. The use of higher rates of N may be required to support the growth of non-fixing crop. The single most important factor affecting the accuracy of this method is finding an appropriate reference crop that matches the legume in its rooting, N-uptake pattern, and duration. Other problems associated with these methods are considered in detail by Chalk (1985), Danso (1985), and Witty and Giller (1991). The commercial analysis of samples presently costs around US $ 10 sample^{-1}, depending on the number of samples.

The BNF can also be measured by the ^{15}N natural abundance method (Shearer and Kohl 1986; Weaver and Danso 1994). The main advantage of this method is that there is no need to apply ^{15}N enriched material to the soil. Most soils have slightly higher ^{15}N abundance than that of the atmosphere. Because of this difference, N_2-fbeing plants have a lower ^{15}N enrichment than non-fixing plants (Bergersen 1980; Kohl et al. 1980; Peoples et al.

1989). It is important to note that the accuracy of the technique will depend on the level of natural ^{15}N abundance of the soil. The delta (δ) ^{15}N units for most soils are between -2 and +15. Levels of $\delta^{15}N$ >6.0 are preferable, although values as low as 2 might still be useful depending on the level of %Ndfa (Unkovitch et al. 1994). Soils with very low or variable $\delta^{15}N$ values will be unsuitable for assessing N_2 fixation. Furthermore, the method requires a precise mass spectrometer and meticulous analytical procedures. The commercial analysis of soils costs slightly more than US $ 10 sample^{-1}.

Estimates of BNF

Most of the estimates of BNF have been made from well-managed experiments particularly on supply of P and control of pests and diseases. Nevertheless the amount of N_2 fixed and the proportion of N derived from fixation vary considerably even amongst different cultivars of the same legume, and also between different environments in which the crops are raised. The differential behaviour of the cultivars of a legume could be due to variability in nodule formation and in rate of biochemical reactions necessary for N_2-fixation, sensitivity to high concentrations of soil N and the duration of active N_2-fixation period.

Based on the studies conducted in India and elsewhere, estimates of BNF in rainy season legumes grown as sole crops with a starter dose of N and an adequate amount of P, or in farmers' fields with minimal inputs, have been made (Table 2).

Table 2: Estimates of biological nitrogen fixation in tropical grain legumes.

Grain legume	N derived from fixation (%)	Method[1]	Reference
Pigeonpea	88-96	ID	Kumar Rao et al. (1987)
Pigeonpea	0-36	NA	Kumar Rao et al. (1996a)
Mung bean	8-90	NA	Peoples et al. (1991)
Mung bean	0-100	NA	Shah et al. (1997)
Mung bean	45-90	NA	Ali et al.(1997)
Black gram	95-98	NA	Peoples et al. (1991)
Black gram	0-100	NA	Shah et al. (1997)
Black gram	71-84	NA	Ali et al. (1997)
Soybean	78-87	NA	Peoples et al. (1991)
Cowpea	54-70	ID	Awonaike et al. (1990)

[1]ID = ^{15}N isotope dilution; NA = ^{15}N natural abundance.

RESIDUAL EFFECTS OF GRAIN LEGUMES

In rice and wheat cropping systems, most of the studies so far conducted on the effect of legumes pertain to green manuring where the combined effects of BNF and organic matter addition have been evaluated. There are only a few direct measurements of the amounts of grain legume N recovered by the succeeding cereals.

Residual Effect of Summer Grain Legumes on Rice

In double cropping, a rice crop is usually grown after winter grain legumes such as chickpea *(Cicer arietinum),* lentil *(Lens culinaris),* and pea (*Pisum sativum)* whereas in intensive rotations involving three crops it is raised after a summer legume such as mung bean, black gram, and cowpea. Studies conducted during 1986/87 to 1991/92 at various locations in the IGP have shown a distinct advantage in rice yields conferred by preceding grain legumes (AICARP 1986-87,1987-88,1988-89; PDCSR 1989-90,1990-91,1991-92). De et al. (1983) obtained rice yields of 4.78 t ha^{-1} after cowpea, 4.50 t ha^{-1} after mung bean, and 4.28 t ha^{-1} after black gram compared to only 3.41 t ha^{-1} after maize fodder. The contribution of these legumes was equivalent to 13-67.5 kg N ha^{-1} applied to rice succeeding maize fodder. Under Kaul (Haryana, India) conditions, rice following summer green manuring with *Sesbania aculeata* and mung bean gave much higher yields compared to rice after fallow and maize fodder (Table 3). Based on regression analysis, the optimum dose of N was 73.6 kg ha^{-1} after *Sesbania,* 66.4 kg ha^{-1} after mung bean, 152.4 kg ha^{-1} after maize fodder, and 151.6 kg ha^{-1} after fallow. This indicated an economy of about 78.0 kg N ha^{-1} after *Sesbania* and 85.2 kg N ha^{-1} after mung bean compared to rice after fallow. The higher rice yields after legumes could be due to addition of about 60 kg N ha^{-1} by *Sesbania* and 30 kg N ha^{-1} by mung bean (based on N turned into soil through stover). Rice after *Sesbania* and mung bean removed more N than rice after maize fodder and fallow indicating greater availability of N in the soil for use by the subsequent crop (Table 3) (Antil et al. 1989).

Table 3: Effect of preceding crops and nitrogen (N) application on grain yield and N uptake of rice, in Kaul, Haryana, India, rainy season 1981 and 1982.

	Grain yield (t ha^{-1}) at different N levels (kg ha^{-1})[1]					
Preceding crop	0	40	80	120	Mean	N-uptake (kg ha^{-1})[2]
Sesbania aculeata	6.12	7.06	7.50	7.66	7.08	126 (189)
Mung bean	6.15	6.96	7.32	7.52	6.99	115 (162)
Maize fodder	4.74	5.77	6.85	7.42	6.19	96 (122)
Fallow	4.38	5.54	6.66	7.31	5.97	94 (94)

[1] Average of 1981 and 1982. No statistical analysis available.

[2] Figures in parentheses indicate total N uptake by both crops of the system.

Source: Antil et al. (1989).

The ability of grain or fodder legumes to fix atmospheric N could be exploited to supplement the N needs of a succeeding cereal crop. Ali (1992) observed that rice yields after mung bean and cowpea were substantially higher compared to rice after fallow at all the levels of applied N, and even where no N was applied (Fig. 1).

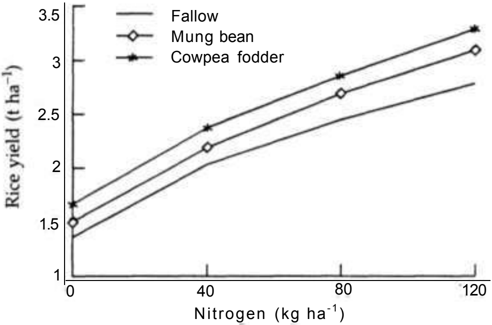


Figure 1: Effect of summer legumes on rice yield in Kanpur, India, rainy season 1987 and 1988.
(Source: Ali 1992).

Residual Effect of Summer and Rainy Season Grain Legumes on Wheat

Wheat is grown as winter/spring crop in IGP and is usually followed by rainy season grain legumes and cereals such as rice, sorghum, maize, and pearl millet *(Pennisetum glaucum).* The productivity and monetary gains in wheat-based systems can be further enhanced by inclusion of a legume during summer (K.S. Gill, Punjab Agricultural University, Ludhiana, personal communication 1989; Faroda 1992). Multilocation experiments conducted at various locations in Uttar Pradesh, Punjab, and West Bengal during 1986/87 to 1991/92 have revealed that yields of wheat were invariably higher after rainy season grain legumes compared to those after rice (AICARP 1986-87, 1987-88, 1988-89; PDCSR 1989-90, 1990-91, 1991-92). This reflects the residual effect of preceding legumes on wheat. Since all these experiments were conducted at the recommended production technology of the component crops of the cropping systems, the N-economy could not be quantified.

Cereal-cereal crop sequences often result in a negative N balance, whereas inclusion of a legume results in a less negative or positive N balance (Rao and Sharma 1978). Singh and Singh (1991) reported that the optimum level of N for wheat was 39.9-57.2 kg ha^{-1} after legumes and 77.8-110.2 kg ha^{-1} after cereals, indicating a reduction in N needs of wheat by 20-70 kg N ha^{-1} after legumes (Fig. 2).

At Faizabad (Uttar Pradesh), the positive residual effect of rainy season grain legumes (mung bean and black gram) was noticed both under optimum and sub-optimum N application in succeeding wheat (Table 4). Black gram had a relatively higher residual effect than mung bean (Yadav and Singh 1986).

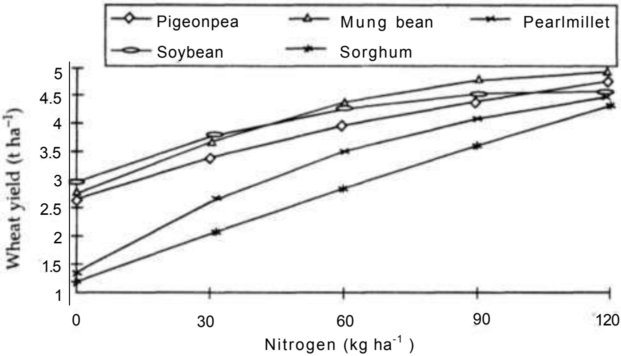


Figure 2: Response of wheat to applied nitrogen (N) after rainy season crops, Hisar, India, postrainy season 1986/87 and 1987/88.
(Source: Singh and Singh 1991).

Table 4: Wheat yields as affected by preceding grain legumes and nitrogen (N) application, Faizabad, Uttar Pradesh, India, postrainy season 1981/82 and 1982/83.

	Wheat yield (t ha^{-1})[1]		
Preceding crop	90 kg N ha^{-1}	120 kg N ha^{-1}	Mean
Fallow	4.43	4.76	4.59
Mung bean	4.55	4.86	4.71
Black gram	4.70	4.94	4.82
Mean[2]	4.63	4.90	4.77

[1] Mean of 1981/82 and 1982/83. No statistical analysis available.
[2] Mean of grain legumes (mung bean and black gram).
Source: Yadav and Singh (1986).

Studies conducted at the Indian Agricultural Research Institute (IARI), New Delhi, India to examine the effect of various rainy season legumes on productivity and N economy in wheat have revealed that the response of wheat to applied N after legumes was quadratic in nature, while it was linear after sorghum (Singh et al. 1993). Cluster bean and black gram had greater residual effects than other legumes when compared with sorghum fodder (Table 5). Wheat required 74.0 kg N ha^{-1} after pigeonpea, 49.4 kg N ha^{-1} after soybean, 58.3 kg N ha^{-1} after groundnut, 42.7 kg N ha^{-1} after black gram, 28.8 kg N ha^{-1} after cluster bean, and 107.3 kg N ha^{-1} after sorghum to produce a targeted grain yield of 4.5 t ha^{-1}. Cluster bean and black gram affected greater N economy (64.6-78.4 kg ha^{-1}) and nutrient removal in subsequent wheat (Fig. 3). Soil studies showed negative N balances in pigeonpea-wheat (-52 kg ha^{-1}) and sorghum-wheat (-91.5 kg ha^{-1}) sequences whereas cluster bean-wheat had the highest positive N balance

Table 5: Wheat yields as affected by preceding rainy season crops (legumes and sorghum) and nitrogen application, New Delhi, India, postrainy season 1986/87 and 1987/88.

Preceding rainy season crop	Yield of rainy season crop ($t\ ha^{-1}$)	Wheat yield ($t\ ha^{-1}$) at different N levels ($kg\ ha^{-1}$)				
			40	80	120	Mean
Pigeonpea	1.57	3.00	3.91	4.56	4.84	4.02
Soybean	1.49	3.34	4.24	4.87	5.15	4.44
Groundnut	1.57	3.37	4.42	4.81	4.93	4.36
Black gram	0.86	3.37	4.51	5.04	5.36	4.57
Cluster bean	2.11	3.70	4.77	5.17	5.27	4.73
Sorghum fodder	72.70	2.88	3.61	4.07	4.67	3.81
Mean		3.25	4.24	4.75	5.04	
LSD (P = 0.05)						
Rainy season crop	0.20					
N levels	0.11					
Interaction effect	0.29					

Source: Singh et al. (1993).

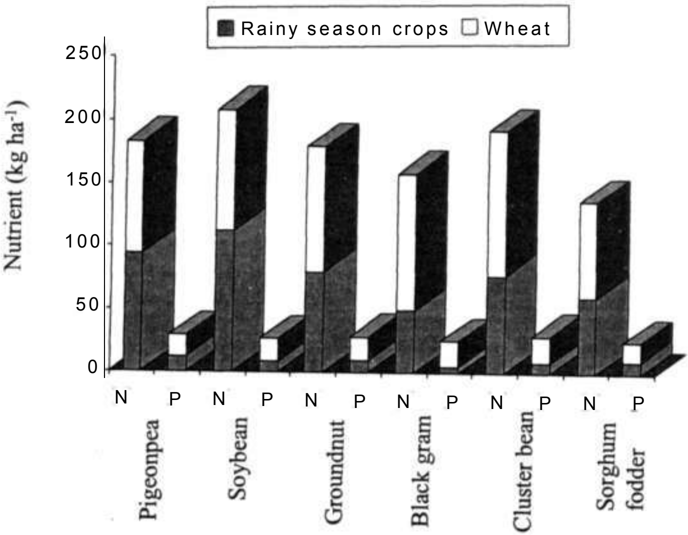


Figure 3: Nutrient (N = nitrogen, P = phosphorus) uptake in rainy season crops and succeeding wheat in New Delhi, India, 1986/87 and 1987/88. *(Source:* Singh et al. 1993)

(+37 kg ha^{-1}) followed by black gram-wheat (+31 kg ha^{-1}) (Singh et al. 1993). Apparent N contribution from soil was maximum in the soybean-wheat sequence and minimum in the black gram-wheat sequence. Available soil P net balance after all the sequences was positive. However, the highest balance was noticed in cluster bean-wheat and the lowest in the sorghum fodder-wheat sequence. In another study at the same location, wheat after an adequately fertilized (20 kg N + 26 kg P ha^{-1}) cowpea fodder crop required only 32 kg N ha^{-1} to produce a targeted yield of 4.5 t ha^{-1} whereas it needed 68 kg N ha^{-1} when cowpea received only half of the recommended fertilizer dose (i.e., 10 kg N + 13 kg P ha^{-1}) (Lal et al. 1978). This study indicates that an adequately fertilized cowpea might have fixed more N and produced more biomass of cowpea, leading to a greater residual effect on succeeding wheat compared to inadequately fertilized cowpea.

In studies conducted at Kanpur (Uttar Pradesh) and Hisar (Haryana), wheat after rainy season legumes responded only up to 80 kg N ha^{-1} whereas favorable responses up to 120 kg N ha^{-1} were observed after fallow, sorghum, and millet (AICPIP 1975-76,1976-77; Kushwaha and Ali 1988). These studies further revealed that the wheat crop without N after cowpea fodder produced a similar yield to that of wheat with 80 kg N ha^{-1} after sorghum at Kanpur. Similarly, unfertilized wheat after mung bean gave the same yield as obtained with 80 kg N ha^{-1} after pearl millet at Hisar. In double cropping, cowpea grown for grain and fodder contributed 24 and 30 kg N ha^{-1} respectively to the following wheat crop under Delhi conditions (Singh et al. 1977; Singh and Nair 1978).

Residual Effect of Grain Legumes in Rice-Wheat Systems

The development of short-duration varieties of rainy season grain legumes in general and mung bean and cowpea in particular has provided a good opportunity to raise a successful crop in the intervening period between harvest of wheat and planting of rice. This practice not only provides about 0.5-1.0 t ha^{-1} of pulse grain but also benefits the succeeding cereal crops through an improvement in N status of the soil. Such a benefit could further be improved by incorporation of mung bean straw in the soil after picking of pods.

The cereal-cereal based cropping systems usually result in negative N balances in the soil even when all the component crops of the system are provided with recommended levels of fertilizers (Rao and Sharma 1978). Inclusion of a legume component in such rotations helps in maintaining the status of soil N. It also improves organic carbon and mineralizable N content of soil (George and Prasad 1989). Multilocation trials at Masodha and Varanasi in Uttar Pradesh and Ludhiana in Punjab have shown higher production potential and net returns in a rice-wheat system by including mung bean (Fig. 4) (AICARP 1982-83, 1983-84, 1984-85).

Studies conducted at Faizabad (Uttar Pradesh) have shown that rice and wheat yields increased by 9.6% and 5.3% respectively by incorporation of

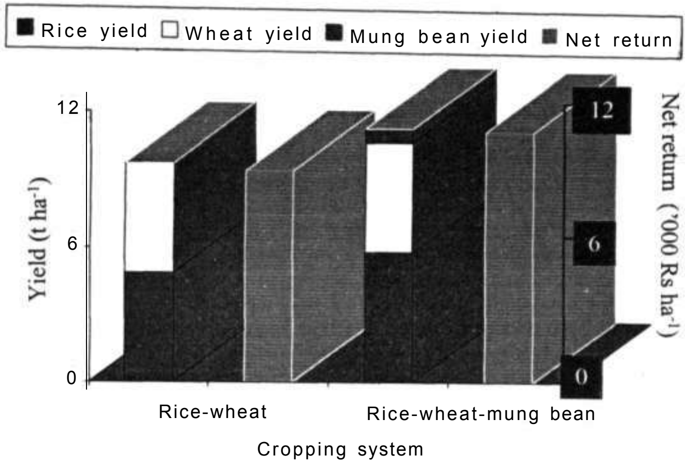


Figure 4: Effect of mung bean on productivity of a rice-wheat system; mean of three locations, Masodha, Varanasi, and Ludhiana in India. *(Source:* AICARP 1982-83, 1983-84, 1984-85)

mung bean stover after picking of pods compared to the rice-wheat system (Hegde 1992). In addition to this, stover incorporation also improved organic carbon content and enhanced the availability of N and micronutrients (Meelu and Rekhi 1981).

On the basis of a number of experiments, Mahapatra et al. (1974) reported that in a mung bean-rice-wheat cropping system, additional grain (pulse) yield of 0.5-1.0 t ha^{-1} and a contribution of 15-20 kg N ha^{-1} to the following rice crop was observed. In a 4-year study at Pantnagar (Uttar Pradesh) comparing three crop sequences, i.e., rice-wheat, rice-wheat-mung bean and rice-wheat-maize + cowpea fodder at recommended levels of fertilizer, the mean combined yield of rice and wheat were similar in all the crop sequences. An additional yield of 0.8 t ha^{-1} of mung bean grain and 30.0 t ha^{-1} of fodder was obtained by raising mung bean and maize + cowpea fodder during summer (Deka et al. 1984). Inclusion of mung bean and maize + cowpea fodder in rice-wheat sequence removed about 85 kg N ha^{-1},10 kg P ha^{-1}, and 53 kg K ha^{-1}; and 108 kg N ha^{-1},21 kg P ha^{-1}, and 84 kg K ha^{-1} respectively, more than the rice-wheat sequence (Deka and Singh 1984). The residual effect of legumes could not be observed in this study because of use of recommended levels of fertilizers to component crops.

Studies conducted at IARI have revealed marked beneficial residual effect of summer legumes on the productivity of rice and also a carry-over effect on succeeding wheat (Table 6). Cowpea green manuring was the most efficient source of N followed by incorporation of mung bean stover after

Table 6: Rice and wheat yields and total productivity as affected by summer legumes in New Delhi, India, 1992-95.

	Grain yield (t ha^{-1}) at different N levels (kg ha^{-1})[1]				
Summer crop[2]	0	40	80	120	Mean
Rice yield (t ha^{-1})					
Fallow	3.40	4.12	4.44	4.65	4.15
Cowpea (GM)	4.25	5.01	5.23	5.35	4.96
Mung bean (SR)	3.59	4.02	4.45	4.79	4.21
Mung bean (SI)	4.16	4.71	4.88	5.15	4.72
Wheat yield (t ha^{-1})					
Fallow	2.50	2.34	4.97	3.14	3.09
Cowpea (GM)	3.60	3.57	3.84	4.04	3.89
Mung bean (SR)	3.11	3.25	3.38	3.66	3.51
Mung bean (SI)	3.49	3.47	3.65	3.79	3.84
Total productivity (t ha^{-1})					
Fallow	5.90	6.46	7,11	*7.79*	6.89
Cowpea (GM)	7.85	8.58	9.07	9.39	8.72
Mung bean (SR)	6.70	7.27	7.83	8.45	7.56
Mung bean (SI)	7.65	8.18	8.53	8.94	8.32

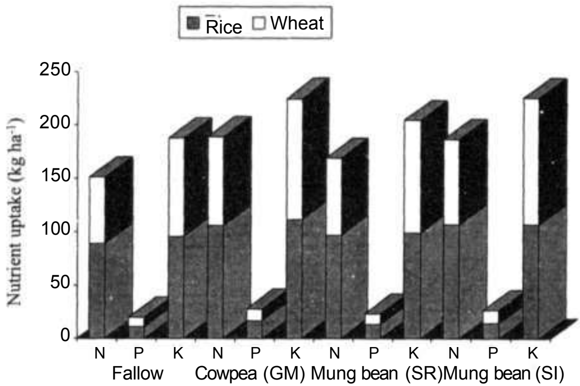
[1]No statistical analysis available.
[2]GM = Green manuring; SR = Stover removal; and SI = Stover incorporation.
Source: Prasad and Mishra (1995).

picking of pods. The yields of rice either with 40 kg N ha"^{1} after mung bean stover incorporation or with 120 kg N ha^{-1} after fallow were comparable indicating a legume advantage of 80 kg N ha^{-1} (Table 6).

Similarly, a wheat crop receiving no fertilizer N after mung bean (with or without stover incorporation) produced almost similar yields to that of wheat following fallow and fertilized with 120 kg N ha^{-1}. The residual effect of legumes on following rice and wheat crops was further apparent from nutrient uptake patterns of these crops (Fig. 5). Legume-based crop sequences caused more removal of NPK by both rice and wheat indicating greater availability of nutrients for use by these crops (Fig. 5) (Prasad and Mishra 1995).

In another study, rice and wheat crops following summer mung bean with its stover incorporation recorded significantly higher yield compared to summer fallow during three crop seasons (Table 7). No marked benefit of mung bean where its stover was removed could be seen in either of the two cereal crops (IARI1995). The grain yield of rice after mung bean was greater than rice after fallow both in presence and absence of applied N (Fig. 6). The root length and root weight density of wheat at 90 days in mung bean residue incorporated plots was less in the upper soil layer (0-15 cm) and more in deeper soil layers than in fallow plots (IARI 1995).

At Faizabad (Uttar Pradesh), green manuring with summer mung bean and incorporation of its stover after picking of pods proved equally effective in increasing the yields of succeeding rice and wheat crops compared with summer fallow (Saxena 1995).



GM = Green manuring, SR = Stover removal, and SI = Stover incorporation

Figure 5: Nutrient uptake in rice-wneat cropping system as affected by summer season legumes (GM = green manuring, SR = stover removal, and SI = stover incorporation), New Delhi, India, 1992-95. (*Source:* Prasad and Mishra 1995)

Table 7: Effect of summer legume (mung bean) on productivity of a rice-wheat cropping system, New Delhi, India, 1992-95.

Summer crop[1]	Grain yield (t ha^{-1}) 1992/93 Mung bean	Rice	Wheat	1993/94 Mung bean	Rice	Wheat	1994/95 Mung bean	Rice	Wheat
Fallow		3.98	3.35	-	4.84	4.30	-	5.19	3.59
Mung bean (SR)	0.53	4.37	3.76	0.51	5.19	4.87	0.54	5.35	3.82
Mung bean (SI)	0.51	4.71	3.96	0.54	5.57	4.78	0.57	5.76	4.09
LSD (P = 0.05)	NS[2]	0.49	0.52	NS	0.43	0.39	NS	0.57	0.33

[1]SR = Stover removal; SI = Stover incorporation.

[2]NS = Not significant.

Source: IARI (1995).

Residual Effect of Summer and Rainy Season Grain Legumes on Other Crops

At IARI, maize grown after incorporation of mung bean stover after picking of pods produced markedly higher grain yield compared with removal of mung bean stover. The economic optimum dose of N in maize was 112.2 kg ha^{-1} where the stover of preceding mung bean was removed as against 83.5 kg ha^{-1} after incorporation of the stover. It indicated an economy of 28.7 kg

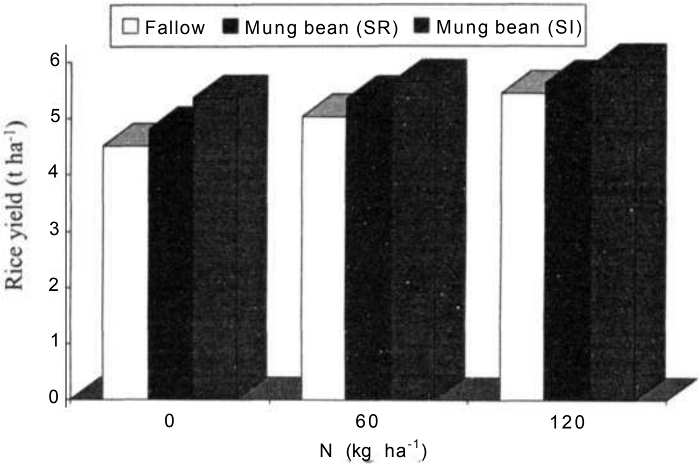


Figure 6: Response of rice to nitrogen (N) after summer mung bean (SR = stover removal, and SI = stover incorporation) New Delhi, India, 1992-95. *(Source:* IARI 1995)

N ha^{-1} with stover incorporation over and above the legume effect of mung bean (Singh 1990). The maize crop after incorporation of mung bean stover removed 9.5 kg more N and 2.1 kg more P ha^{-1} compared with maize grown after stover removal of mung bean. In other studies at the same location, barley *(Hordeum vulgare)* grown after rainy season legumes [cowpea, cluster bean, soybean, and moth bean *(Vigna aconitifolia)]* gave markedly higher yield compared with barley after pearl millet (IARI1980). Pearl millet following mung bean, cowpea, groundnut, and pigeonpea yielded higher than pearl millet after pearl millet (Giri and De 1979). Mustard *(Brassica* sp.) removed more of N and P and produced higher seed yield after mung bean and black gram compared with mustard after fallow. The soil had higher available N and P after the harvest of rainy season legumes than fallow (Thakur 1979).

In most of the studies on the residual effect of summer and rainy season grain and fodder legumes, an economy of 20-60 kg N ha^{-1} could be affected in succeeding cereals (IARI 1980; Peoples and Herridge 1990).

MECHANISM OF RESIDUAL EFFECT

Nutrient Cycling

Nair et al. (1973) worked on various intensive multiple cropping sequences including rice-wheat-mung bean in northern India and noticed that crop removal exceeded the addition of N especially in legume-based systems. The available N status of the soil did not show any decline but registered a slight increase after the legumes (mung bean and soybean) indicating no soil N stress. Excess removal by crops also indicates the presence of a sufficient amount of N in soil. The addition of N (BNF and soil N) through appreciable amounts of roots and stubbles and leaf fall of legumes and perhaps better cycling of N in residues and soil may partially mitigate the N removal by these crops.

In a study conducted at Ludhiana (Punjab), no appreciable change in available NPK status of soil was noticed after three cycles of a rice-wheat-mung bean sequence. There was, however, some decline in organic carbon content of soil (Meelu et al. 1979). In a 2-cycle sequence of rice-wheat-mung bean at Faizabad (Uttar Pradesh), the soil available NPK status was slightly improved but organic carbon content showed a decline (Ram Newaj and Yadav 1994). Monitoring of NPK status of soil in a 2-cycle sequence of monoculture rice, rice-wheat, and rice-wheat-mung bean showed a negative balance of P in all the sequences and N in rice monoculture and rice-wheat systems. There was, however, a positive balance in respect of soil K in all the sequences, being maximum in the three crop sequence (Prasad and Kerketta 1991). The inclusion of mung bean in the rice-wheat system, possibly through BNF contribution, was responsible for the positive N balance.

In a study conducted over three years, mung bean green manuring or incorporation of mung bean stover after picking of pods in rice-wheat system considerably improved organic carbon content and available P status of soil but decreased available N and K status (Saxena 1995). The differential behavior of a legume in influencing the fertility status of soil largely depends on growth of the legume and yields of the succeeding cereals. Higher yield of cereals may remove large amounts of nutrients leaving the soil under nutrient stress (Saxena 1995). Mann (1988) also observed improved organic matter and available P status of soil with *Sesbania* green manure.

In a rice-wheat system, compared with fallow, incorporation of summer mung bean stover improved the organic carbon content during subsequent rice growth period but showed a substantial decline at rice harvest. There was gradual improvement during the succeeding wheat growth period and harvest of the second rice crop. Stover incorporation showed much higher soil available P compared to fallow plots at the harvest of both rice and wheat (IARI 1995). The improvement in available P may be due to root exudates capable of mobilizing sparingly soluble P in soil (Takaji 1991). Stover incorporation had no effect on Zn, Mn, Fe, and copper (Cu) content of soil throughout the course of such studies (IARI 1995).

In a summer mung bean-maize sequence, soil maintained a higher level of total N and available P than its initial status even at the harvest of maize (Singh 1990). Stover incorporation of mung bean further improved the status of these nutrients and also the organic carbon content.

The overall improvement in available N and P status of soil during three cycles of rice-wheat sequence by raising a summer mung bean crop resulted in a marked beneficial residual effect on these crops (Prasad and Mishra 1995). The effects were, however, more pronounced with stover incorporation of mung bean.

Physical Properties of Soil

There have been very few studies conducted specifically to know the effect of legume components of the rice and/or wheat system on soil physical properties. The puddling operation in rice cultivation destroys the soil structure and results in poor soil physical conditions with low water stable aggregates and low infiltration rates. In a study involving various cropping systems at Pantnagar, India and conducted over a period of nine years in a silty clay loam, it was observed that water stable aggregates declined by 21% in a rice-wheat-cowpea system compared to a fallow system. The better soil aggregation in the fallow system increased hydraulic conductivity to 1.5-6.0 times greater than in the cropped system (Kumar and Tripathi 1990).

Meelu et al. (1979) compared maize-wheat-mung bean and rice-wheat-mung bean crop sequences and observed that after three cycles, the soil in crop sequence involving maize had higher water intake rate, water storage in 0-180 cm soil layer, and water stable aggregates of 0.1 to 0.5 mm compared to the system having rice. However, the rice-wheat-mung bean sequence recorded high electricial conductivity (EC), bulk density, dispersion ratio, and water stable aggregates of >0.5 mm. Higher bulk density and low infiltration rate was also reported in a rice-wheat-mung bean system over a pigeonpea-wheat-mung bean sequence (Ram Newaj and Yadav 1994). These studies do not really indicate any positive effect of legume on soil physical properties, but clearly indicate a negative effect of rice.

Incorporation of crop residues after rice or green manuring improves the physical condition of the soil. Incorporation of mung bean stover in a rice-wheat-mung bean sequence resulted in lower bulk density and higher hydraulic conductivity (Table 8) compared to fallow during the course of three cycles of this sequence (1992-95). At the harvest of the last wheat crop (1994-95), plots with stover incorporation of mung bean had higher infiltration rate, mean weight diameter of soil aggregates at 0-15 cm and 15-30 cm soil depth, and percentage of water stable aggregates of >0.25 mm (IARI 1995).

Biological Properties of Soil

In a rice-wheat system, inclusion of summer mung bean with or without its residue incorporation resulted in a higher soil microbial population and biomass when compared to fallow (Table 9). The effects were, however, more pronounced with residue incorporation. Residue incorporation also resulted in more of CO_2 evolution and dehydrogenase activity in uppermost soil layer of 0-15 cm during six sampling dates between 1993 and 1995 thus indicating increased microbial activity. The increased microbial activity

Table 8: Effect of summer legume on bulk density and hydraulic conductivity of soil in a rice-wheat system, New Delhi, India, 1993-95.

	Bulk density ($mg\ m^{-3}$)		Hydraulic conductivity ($cm\ h^{-1}$)	
Treatment[1]	0-15 cm	15-30 cm	0-15 cm	15-30 cm
50 days after puddling (1993)				
Fallow	1.59	1.62	3.37	3.30
Mung bean (SI)[2]	1.57	1.62	3.74	3.67
Rice harvest (1993)				
Fallow	159	1.63	3.90	3.21
Mung bean (SI)	1.54	1.60	4.01	4.16
Wheat harvest (1993/94)				
Fallow	1.59	1.64	3.92	3.75
Mung bean (SI)	1.54	1.60	5.62	5.36
Wheat harvest (1994/95)				
Fallow	1.56	1.60	3.76	3.60
Mung bean (SI)	1.51	1.55	4.39	4.07

[1]Soil tested at depths of 0-15 cm and 15-30 cm. Statistical analysis of the data is not available.

[2]SI = Stover incorporation.

Source: IARI (1995).

might influence mineralization and immobilization of nutrients such as N and P depending on the composition of the residues and environment. These results indicate that inclusion of a legume in the rice-wheat system improves soil microbial biomass and their activity that could be vital for long-term soil health and productivity (Table 9) (IARI 1995).

Table 9: Effect of a summer legume (mung bean) on microbial biomass and population in soil at 0-15 cm depth, New Delhi, India, 1993-94.[1]

	Microbial biomass ($\mu g\ g^{-1}$ soil)		Microbial population (number g^{-1} soil)					
Treatment[2]	Wheat harvest	Rice harvest	Bacteria x 10^5	Acrino-mycetes x 10^4	Fungi x 10^4	Azoto-bacter x 10^2	Azosp-irillum x 10^4	PSB[3] x 10^2
Rice crop (1993)								
Fallow	185	219	55	0.5	0.2	25	1.2	-
Mung bean (SR)	198	225	115	1.5	1.0	92	18.7	4.0
Mung bean (SI)	244	315	195	6.5	1.8	210	41.7	6.5
Wheat crop (1993/94)								
Fallow			40	0.4	0.5	14	0.015	1.2
Mung bean (SR)			42	38.0	0.6	35	0.250	2.5
Mung bean (SI)			65	140.0	0.9	65	0.750	4.2

[1]Statistical analysis of the data is not available.

[2]SR = Stover removal; and SI = Stover incorporation.

[3]PSB = Phosphate solubilizing bacteria.

Source: IARI (1995).

Pests and diseases

No systematic information on the effect of inclusion of a legume in rice-wheat systems on incidence of pests and diseases is available. Some studies have shown that growing of a legume and its residue incorporation in the soil has no effect on the incidence of *Pyrilla perpusilla,* gandhi bug *(Leptocorisa* spp.), and leaf folder *(Cnaphalocrocis medinalis)* in rice and aphid *(Sitobion averae* and *Rhopalosiphum* spp.) incidence in wheat (IARI 1995). Rice crops showed severe infestation of fusariosis *(Fusarium moniliforme)* and sheath blight *(Rhizoctonia solani)* in summer fallow plots compared to legume plots. Incidence of leaf rust *(Puccinia recondita)* in wheat was reduced by growing mung bean in summer (IARI 1995). Residue incorporation of mung bean reduced the population of nematodes *(Tylenchorhynchus* spp.) at all the stages of rice growth (IARI 1995).

CONCLUSION

With the development of high-yielding fertilizer-responsive cultivars of wheat in the late sixties and those of rice in the early seventies, and the extension of irrigation facilities in IGP, the cropping pattern of IGP made a distinct shift in favor of rice-wheat systems. However, continuous growing of these two cereals in a year has led to soil sickness problems. There are clear indications that yield of both these crops in the system are showing a declining trend in this region (Hegde and Sarkar 1992). Results of experiments conducted at various locations have indicated that inclusion of legume either for green manuring or residue incorporation after obtaining the grain can check the resource degradation and sustain the productivity of rice-wheat system by maintaining physico-chemical and biological properties of the soil.

FUTURE RESEARCH NEEDS

The role of legumes in rice and /or wheat systems has to be redefined in view of soil and crop health with detailed investigations on periodic shifts in soil fertility, productivity, weed flora, insect pests, and disease incidence, and soil biota. There is a need to explore the posibilities of incorporating legumes prior to direct seeded rice, growing crops such as *Casuarina* and pigeonpea as alley crops in rice fields, and also incorporating biomass produced elsewhere. There is also a need to determine the possiblility of raising a legume such as cowpea for addition of biomass in between a short-duration rice (harvested in September) and late sown wheat (planted in December) under specific situations such as in eastern Uttar Pradesh and parts of Bihar. Besides, short-duration and dwarf legumes such as *Melilotus* spp. and *Vicia* spp. which degenerate quickly leaving substantial biomass could be identified for raising in association with rice and wheat crops.

In most of the experiments conducted so far, the effects of legumes on physical, chemical, and biological properties of soil, productivity of the system, and the incidence of pests and diseases have been studied over a short period only. There is a need to quantify these effects of grain legumes/ crop residues/green manures/farm-yard manure on a long-term basis to understand the sustainability of the rice and/or wheat system. Fertilizer economy due to residual effects of legumes also needs to be better quantified so that the dose of fertilizer in succeeding cereals can be curtailed. For this, crop and systems models need to be developed and tested to predict the residual effects of legumes in crop rotations. One approach could be the use of a static model involving cultivation of legume followed by a cereal, estimating nutrient (e.g., N) inputs and outputs, and N saving to the soil/ residual N benefit to the following crop. The static model considers the growth of the crop as a single step in which yield potential is estimated from an integrated measure of the environment such as total rainfall. Alternatively, dynamic models appear to be better as they account for fundamental processes, and so, in principle should be transferable to other situations and be useful in evaluating environmental consequences as well as production.

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4

Direct and Residual Effects from Forage and Green Manure Legumes in Rice-based Cropping Systems

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ABSTRACT

Direct benefits from green manure legumes in rice-based cropping systems have been recognized for thousands of years. Even though the practice of this once common excercise has declined, green manure legumes consistently have been recommended for regenerating depleted soil resources and increasing yields. Forage legumes provide another alternative for improving the soil resource base, while also supplying the much needed fodder material for livestock. Recently there has been renewed interest in legumes, especially for the rice-wheat cropping systems of South Asia, where stagnant or declining yields under intensive, continuous cropping have raised concerns about sustainability and possible adverse environmental impacts. This paper summarizes and evaluates current knowledge about direct and residual effects from green manure and forage legumes used in the rice-based cropping systems of India, Nepal, Bangladesh, and Pakistan.

Most research citings focused on the direct and residual nitrogen contributions from green manure and forage legumes. Additional yield potential benefits not attributable to nitrogen (N) also were noted, but little systematic research has been undertaken to determine the non-N benefits from these legumes. Management constraints and cost effectiveness may outweigh the N benefits from legumes; even if the cost of inorganic N fertilizer increases in the near future. Resolving practical difficulties and determining the direct and residual non-N benefits is essential for promoting legumes in rice-based cropping systems as a sustainable agricultural practice.

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INTRODUCTION

More than half of the world's population of over 5 billion people live in Asia, where rice *(Oryza sativa)* is the major staple food. About 149 million ha of land in the world are under rice cultivation of which 133 million ha is in Asia. Bangladesh, China, India, Indonesia, Myanmar, and Pakistan are the important rice-producing countries in Asia (Table 1).

Table 1: Area, production, and yield of rice and wheat in Asia.

	Area (million ha)		Production (million t)		Yield (kg ha^{-1})	
Country	Rice	Wheat	Rice	Wheat	Rice	Wheat
World	149.1	214.1	530.0	535.8	3554	2502
Asia	132.5	75.8	480.5	216.8	3626	2527
Bangladesh	9.9	0.6	27.5	1.1	2796	1998
China	32.7	29.5	175.6	102.1	5364	3458
India	41.5	24.4	117.6	57.8	2834	2365
Indonesia	10.7	-	46.9	-	4368	-
Japan	2.3	0.2	13.1	0.6	5706	3429
Myanmar	6.5	-	19.1	-	2942	-
Nepal	1.4	0.6	3.3	0.8	2776	1342
Pakistan	2.2	8.1	5.5	15.1	2500	1876
Sri Lanka	0.8	-	2.6	-	3130	

Source: FAO (1995).

To meet the future demand for rice, it is projected that world annual production must increase from 530 million t to 758 million t by AD 2020—a 43% increase in 26 years or 1.65% yr^{-1}. Rice is grown under different cropping systems, but among the various agricultural production systems, rice-wheat *(Triticum aestivum)* is agroecologically and socioeconomically important in South and Southeast Asia. The rice-wheat rotation is practiced on more than 22 million ha in Asia which includes China (10.3 million ha), India (9.6 million ha), Pakistan (1.5 million ha), Bangladesh (0.5 million ha), and Nepal (0.5 million ha). In each of these five countries, rice and wheat together account for 70-100% of the total cereal production, and 56-94% of daily caloric intake. Globally, the rice-wheat rotation provides staples for about 20% of the world's population.

Direct benefits from green manure legumes (GMLs) in rice-based cropping systems have been recognized and utilized by farmers for at least 3000 years in China (Lizhi 1988) and as far back as 1000 BC in the Indian subcontinent (Raychaudhuri 1960). However, what was once a common practice has been declining, especially since the Green Revolution. Although little data is available about current farmer practice, it appears that <5% of the rice area in Asia (6 million ha) receives additions of green manure (Garrity and Flinn 1988; Lizhi 1988). A symposium held at the International Rice

Research Institute (IRRI), Philippines in 1987 identified the following major factors as responsible for the decline in green manure use: (1) low cost inorganic nitrogen (N) fertilizers; (2) increased availability and convenience in handling inorganic fertilizers; (3) more profitable alternate uses for land; (4) low legume seed viability and high costs; (5) difficulties in incorporating green manure biomass; and (6) labor shortages (IRRI 1988). Despite these constraints, it is anticipated that use of green manure will expand in the near future because of the rising demand for and costs of inorganic fertilizers (Meelu et al. 1992b). More importantly green manure is being advocated as a sustainable agricultural practice to regenerate depleted soil resources and boost declining yields. This approach is especially pertinent in South and Southeast Asia, where recent observations of stagnant or declining yields under intensive, continuous rice cropping and in the rice-wheat rotation, have raised concerns about long-term sustainability and possible adverse environmental impacts of these systems (Flinn and DeDatta 1984; Giri et al. 1993).

In contrast to GMLs, forage legume cultivation has never been very extensive in South Asia, even though there is a significant deficit of fodder material in the region. In India alone, it is estimated that 1136 million t of green forage will be required for the country's livestock populations by the year 2000 (Singh 1988). Most farmers in the region invest very little capital in animal feed, often supplying weeds or crop residues rather than quality forages. Forage legumes fed along with crop residues significantly increase live weight gains and animal productivity (Moog 1986; Peoples and Herridge 1990). Furthermore, forage legumes have the potential for improving soil N status through N_2 fixation (Vallis 1972), improving soil physical conditions and reducing some pest/pathogen pressures in rotations. Despite these benefits, forage legume cultivation in South Asia is still very limited, primarily because of land competition with intensive cereal production, e.g., only 4% of India's cultivated area is devoted to forage production (Singh 1988). Integrating forage legumes into existing cropping systems through intercrops or relay crops may provide an attractive option for farmers to improve soil fertility status without sacrificing food crop areas (Carangal et al. 1994; Ladha et al. 1996).

While much research has been carried out on green manure, efforts have been unidirectional, focusing on N benefits. This knowledge has not been enough to convince most farmers to adopt the practice of green manuring. The objective of this paper is to summarize the achievements and understanding of past research on the direct and residual effects from GMLs and forage legumes, while also pointing the way for future technical work to encourage farmers to utilize legumes in their cropping systems.

GREEN MANURE AND FORAGE LEGUME SPECIES

Legumes utilized as green manures in rice-based cropping systems can be broadly characterized as pre-rice or post-rice (Garrity and Flinn 1988).

Species such as *Crotalaria juncea* (sunn hemp), *Sesbania aculeata, S. rostrata, Cyamopsis tetragonoloba* (cluster bean), and *Vigna unguiculata* (cowpea) have been used as 45-60 day catch crops in the pre-rice phase between winter and rainy season cereals. Biomass from these legumes is incorporated into the soil at the onset of monsoon, just before rice transplanting. Post-rice species include forage legumes such as *Trifolium alexandrinum, T. repens* (white clover), *Clitoria ternatea, Desmanthus virgatus, Cyamopsis tetragonoloba,* and *Macroptilium atropurpureum* which are substituted for staple winter cereal crops (Meelu and Rekhi 1981; De et al. 1983; Bhattarai and Maskey 1996; Ladha et al. 1996). Other GMLs such as *Astragalus sinicus* and *Indigofera tinctoria* can also be grown during this period, either cropped alone or relay cropped with dry season/winter crops (Lizhi 1988; Garrity et al. 1994). Most grain legumes are also grown during the post-rice phase, after which residues from the grain legumes are often used as fodder or green manure for rice.

BIOMASS AND NITROGEN ACCUMULATION

Examples of biomass and N accumulation for GMLs are tabulated in Table 2 and in several reviews on legumes in rice cropping systems (Ladha et al.

Table 2: Biomass and nitrogen (N) accumulation by green manure legumes.

Legume	Biomass dry matter (t ha^{-1})	N accumulation (kg ha^{-1})	Age (days)	Reference
Cowpea	23.2 (F)	74	60	Sanyasi (1952)
Cowpea	2.1	49	49	Singh (1962)
Cowpea	-	74	45	Morris et al. (1986)
Cowpea	2.3-2.5	62-70	45	John et al. (1989)
Cowpea	2.8-3.1	67-69	40	John et al. (1992)
Cowpea	0.6-3.6	18-69	30-60	Meelu et al. (1992b)
Cluster bean	1.3	25	49	Singh (1962)
Cluster bean	-	56	45	Mann (1988)
Cluster bean	3.8	87	60	Beri et al. (1989a)
Indigofera sp.	0.03-4.7	0.9-110	30-60	Meelu et al. (1992b)
Lablab	0.9-4.5	25-84	30-60	Meelu et al. (1992b)
Mung bean	1.9	42	49	Singh (1962)
Mung bean	-	86	40	Morris et al. (1986)
Mung bean	1.1-4.7	32-136	30-60	Meelu et al. (1992b)
Mung bean	12.8 (F)	-	-	Maskey and Bhattarai (1995)
Pillipesara	25.0 (F)	102	60	Sanyasi (1952)
Pigeonpea	0.5-3.6	12-76	30-60	Meelu et al. (1992b)
Sesbania sp.	7-8 (F)	40	-	Alam et al. (1984)
Sesbania sp.	-	97-149	50	Sharma and Mittra (1990)
Sesbania sp.	2-6	70-169	45-60	Ahmed (1992)

(Contd.)

Table 2 *(Contd.)*

Legume	Biomass dry matter (t ha^{-1})	N accumulation (kg ha^{-1})	Age (days)	Reference
S. aculeata	23.2 (F)	133	60	Sanyasi (1952)
S. aculeata	-	57-141	M[2]	Chapman and Myers (1987)
S. aculeata	-	68	45	Mann (1988)
S. aculeata	5.4	110	60	Beri et al. (1989a)
S. aculeata	5.0	108	60	Beri et al. (1989b)
S. aculeata	4.3-4.8	102-107	60	Beri et al. (1989b)
S. aculeata	2.8-9.9	81-225	30-60	Meelu et al. (1992b)
S. cannabina	18-37 (F)	98-165	45-65	Bhardwaj and Dev (1985)
S. cannabina	23.6 (F)	-	-	Maskey and Bhattarai (1995)
S. cannabina	-	160	60	Patel et al. (1996)
S. cannabina	-	209	ST[2]	Patel et al. (1996)
S. rostrata	-	45-83	45	Buresh et al. (1993)
S. rostrata	-	161-227	60	Buresh et al. (1993)
S. rostrata	21.6(F)	-	-	Maskey and Bhattarai (1995)
S. rostrata	-	67	60	Patel et al. (1996)
S. rostrata	-	307	ST	Patel et al. (1996)
Soybean	0.7-7.9	19-141	30-60	Meelu et al. (1992b)
Sunn hemp	0.6 (F)	134	60	Sanyasi (1952)
Sunn hemp	2.4	63	28	Khan and Mathur (1957)
Sunn hemp	4.4	99	42	Khan and Mathur (1957)
Sunn hemp	6.6	140	56	Khan and Mathur (1957)
Sunn hemp	3.4	74	49	Singh (1962)
Sunn hemp	10.9 (F)	-	56	Vachhani and Murty (1964)
Sunn hemp	10-15 (F)	70-100	-	Hoque (1977)
Sunn hemp	5.4	110	60	Beri et al. (1989a)
Sunn hemp	6.9	113	60	Beri et al. (1989a)
Sunn hemp	-	57-98	55	Sharma and Mittra (1990)
Sunn hemp	2.4-8.5	69-169	30-60	Meelu et al. (1992b)

[1]F = Fresh weight.

[2]M = Mature; ST = Stem transplanted.

1988; Buresh and DeDatta 1991; Yadvinder-Singh et al. 1991; Becker et al. 1995). What is noteworthy is how widely these quantities vary; biomass of GMLs ranges from 0.6 t ha^{-1} to 37 t ha^{-1} fresh weight or 0.03 t ha^{-1} to 9.9 t ha^{-1} dry weight, while N accumulations vary from 0.9 kg N ha^{-1} to 307 kg N ha^{-1}. Likewise for forage legumes, regrowth following the last cutting can add 1.1-7.4 t ha^{-1} dry weight and 81-162 kg N ha^{-1}, even after taking 2-7 cuttings for animal feed (Carangal et al. 1994; Ladha et al. 1996). Several factors influence legume biomass and N content, including environmental adaptability, soil fertility, inoculation, and growth duration (Buresh and DeDatta 1991). For example, *Sesbania* tolerates a wide range of climatic conditions including waterlogged soils; however, *Vigna unguiculata, Crotalaria juncea,* and *Cyamopsis tetragonoloba* do not grow well in flooded environments and produce more biomass under drier soil conditions (Veeraswamy and

Kunjamma 1958; Vachhani and Murty 1964; Singh et al. 1981). Small applications of phosphorus (P) (13-26 kg ha^{-1}) and N (15-25 kg ha^{-1}) fertilizers may increase GML biomass (dry weight) up to 1.2 t ha^{-1} and N accumulation up to 30 kg N ha^{-1}, particularly in soils of low fertility (Yadvinder-Singh et al. 1991). Likewise appropriate strains of rhizobia inoculum significantly enhance N_2 fixation (Ladha et al. 1989) and legume biomass by as much as 67% over uninoculated controls (Hossain et al. 1995). Several investigators in Bangladesh have also reported increased uptake of P and sulfur (S) after inoculating several legume species (Bhuiya et al. 1983; Sattar et al. 1994). Finally, Yadvinder-Singh et al. (1991) observed that N content in legume green manures (LGMs) was also affected by the age of the green manure, with optimal levels at 45 days and declining percentages in 60-day-old green manure.

Despite this understanding of the agronomic elements important for good GML productivity, other areas remain to be addressed. Availability of legume seed is still a major constraint, along with lack of equipment for planting and incorporating GMLs, and high variability in green manure productivity which makes the practice too risky for farmers (Palaniappan and Budhar 1994; Saraf et al. 1998). Issues such as pest problems and adaptation to marginal soils and environments need to be considered to make GMLs more desirable to farmers (Becker et al. 1995). One approach to answering this need is to evaluate a greater range of legume species as green manure in several different soil-climate environments. In our review of experiments with GMLs and rice, eight species of legumes were utilized as green manure, and more than 50% of the experiments were with *Sesbania.* Although it is recognized that *Sesbania* spp. are tolerant of a wide range of environmental and edaphic conditions, greater knowledge of the use and environmental adaptability of other legume species would provide more options to farmers for fitting legumes into different ecological niches, thereby encouraging adoption. Such efforts should also include plant breeding work to address some of the pest and pathogen problems of legumes and to capitalize on the genetic potential of a diverse number of species.

ESTIMATES OF BIOLOGICAL NITROGEN FIXATION

The ability of leguminous plants to biologically fix atmospheric N is an important asset providing a relatively low cost method for replacing N removed through agriculture and for building soil N pools. Much effort has been expended measuring N_2 fixation rates to determine the limitations on legume productivity or biological nitrogen fixation (BNF) capacity. The relative merits and problems with various measurement techniques have been thoroughly analyzed by Ladha et al. (1988) and Peoples and Herridge (1990). Likewise, strategies for optimizing BNF as well as legume productivity have also been addressed by Peoples et al. (1995b) and need not be restated here.

Surveys of the literature by Becker et al. (1995) and Peoples et al. (1995a) indicate that the proportion of GML plant N derived from the atmosphere averages 75-80% ranging from 13% to 100%. The amount of N fixed by each crop ranges from 70 kg N ha^{-1} to 324 kg N ha^{-1}. Forage legumes also fix a considerable amount of atmospheric N (about 60-100%), generating up to 380 kg N ha^{-1} (Peoples et al. 1995a). Ladha et al. (1996) found that the quantity of forage residue remaining for soil incorporation varied between 80 kg N ha^{-1} and 143 kg N ha^{-1}.

DIRECT EFFECTS FROM FORAGE AND GREEN MANURE LEGUMES

There is little doubt that GML or forage legume residues produce significant yield increases in a succeeding rice crop. Direct effects, as documented by numerous authors, are exemplified in Table 3 and are also well summarized in review articles by Yadvinder-Singh et al. (1991) and Becker et al. (1995). Briefly, yield responses from soils amended with green manures range from 0.4 t ha^{-1} to 4.1 t ha^{-1} relative to controls without green manure, with low-yielding rice varieties generally showing less of a response (average 0.24 t ha^{-1}) than high-yielding varieties (average 1.7 t ha^{-1}). Yield increases of 0.6-2.4 t ha^{-1} have been recorded following forage legumes (Carangal et al. 1994; Ladha et al. 1996). As expected, high grain yields are often accompanied by increases in plant height, tiller number, productive tillers, or straw yields (Ahmed 1987; Mridha 1987).

The extent to which GMLs contribute to increased rice yields is dependent on several factors. Gu and Wen (1981) reported that yield responses differed according to soil fertility levels. In low fertility soils, rice yields increased by 78%, while on high fertility soils yield increase was only 22%. Likewise Yadvinder-Singh et al. (1991) observed that soils of coarse texture and low organic matter content exhibited a greater response to GMLs than did higher fertility soils. These observations indicate that there are significant effects of green manures on the size and dynamics of active soil organic matter, which supports an active soil biology. Further research attention should be given to this area, considering that low soil organic matter levels are often identified as the major constraint to the sustainability of the rice-wheat cropping system (RWCS).

Incorporation time is another pertinent consideration, because optimal use of LGM N requires synchrony between its mineralization and plant uptake. Traditionally green manures are incorporated into the soil 2-4 weeks prior to rice transplanting (Yadvinder-Singh et al. 1991). To ensure adequate decomposition time, farmers would have to sow the legume at the same time as harvest of the winter cereal crop, competing for time and labor between the two operations (Bhatti et al. 1985). Furthermore several studies from India on light-textured soils indicate that a transplanting delay of 15-20 days after incorporation significantly reduced rice yields by 0.5-1.54 t ha"^{1} (Beri and Meelu 1981; Bhardwaj 1982; Ghai et al. 1988; Beri et al. 1989b).

Table 3: Rice grain yield response to legume green manuring.

Legume	Age (days)	Rice grain yield (t ha^{-1}) -LGM	+LGM	Increase in yield over control (%)	Reference
Aeschynomene afraspera/A. nilotica	49	4.8	8.9	84	Alazard and Becker (1987)
Berseem		5.3 (T)[1]	9.0 (T)	70	Pandey et al. (1998)
Cluster bean	45	1.6	3.0	91	Mann (1988)
Cowpea/mung bean	42	2.1	4.1	95	Morris et al. (1986)
Cowpea	45	3.3	4.4	33	John et al. (1989)
Mung bean	-	3.1	4.5	47	Maskey and Bhattarai (1995)
Milk vetch	-	2.3	4.2	83	Yamazaki (1959)
Milk vetch	-	4.2	5.1	22	Gu and Wen (1981)
Milk vetch	-	3.1	4.2	35	Jiao et al. (1986)
Milk vetch	-	5.7	6.8	19	Chen (1988)
Milk vetch	-	2.9	4.2	45	Ishikawa (1988)
Sesbania aculeata	-	2.2	2.6	19	Sahu and Nayak (1971)
S. aculeata	66	2.6	5.6	114	Dargan et al. (1975)
S. aculeata	50	1.6	2.7	74	Tiwari et al. (1980b)
S. aculeata	35	2.5	3.7	45	Arunin et al. (1982)
S. aculeata	-	1.4	2.3	68	Bhatti et al. (1985)
S. aculeata	50	3.3	6.1	85	Ghai et al. (1988)
S. aculeata	56	4.5	6.1	36	Antil et al. (1988)
S. aculeata	45	1.6	3.2	104	Mann (1988)
S. aculeata	60	2.9	4.0	38	Ramaswami et al. (1988)
S. aculeata	-	1.7	2.1	20	Roy et al. (1988)
S. aculeata	60	2.7	5.8	115	Beri et al. (1989b)
S. aculeata	55	2.0	2.9	51	Mann and Ashraf (In press)
S. aculeata/sunn hemp	60	3.2	4.0	23	Bhardwaj et al. (1981)
S. aculeata/sunn hemp	56	2.6	3.7	41	Sharma and Mittra (1988)
S. aculeata/sunn hemp/ cowpea/cluster bean	60	2.7	5.5	105	Beri et al. (1989a)
S. cannabina	-	3.3	3.9	17	Pandey (1983)
S. cannabina	48	1.8	3.5	92	Morris et al. (1989)
S. cannabina	-	3.1	4.9	60	Maskey and Bhattarai (1995)
S. cannabina	60	3.3	4.7	42	Bhattarai and Maskey (1996)
S. rostrata	-	2.3	4.5	46	Diack (1986)
S. rostrata	48	1.8	3.5	94	Morris et al. (1989)
S. rostrata	49	4.2	5.9	40	Becker (1990)
S. rostrata	-	3.1	4.2	38	Maskey and Bhattarai (1995)
S. rostrata	60	3.3	4.5	36	Bhattarai and Maskey (1996)
S. rostrata/sunn hemp	-	2.4	3.1	29	Rabindra et al. (1989)
S. sesban	84	2.0	4.0	102	Palm et al. (1988)
S. speciosa	-	1.3	2.3	84	Swasdee et al. (1976)
Sunn hemp	-	3.0	3.6	20	Roy et al. (1988)
White clover	-	5.3 (T)	13.1 (T)	147	Pandey et al. (1998)

1. T = Total rice biomass.

Such yield losses were probably caused by nitrate losses via leaching or denitrification (Beri et al. 1989b). However, in other experiments on saline sodic or heavier clay soils, a 1-2 week decomposition period either increased or did not affect rice yields (Vachhani and Murty 1964; Tiwari et al. 1980b; Swarup 1987).

Much research has also been devoted to investigating the role of LGM composition or quality on rice yield responses. Carbon (C)-to-N and lignin-to-fiber ratios as well as polyphenolic content have all been associated with the decomposition/N mineralization rates of green manures (Shi et al. 1981; Palm et al. 1988; Palm and Sanchez 1990). Incubation experiments in unplanted flooded soils have shown that N mineralization from LGMs varies with N (Ito and Watanabe 1985) as well as lignin contents (Shi et al. 1981; Nagarajah et al. 1989). Several comparison studies have been undertaken to assess the direct benefits from LGMs of differing quality, i.e., different legume species (Bhardwaj et al. 1981; Beri et al. 1989a; Chaudhary 1990; Meelu et al. 1992b; Diekmann et al. 1993; Kolar et al. 1993; Kundu et al. 1993; Becker et al. 1994b). While differences in N uptake between species were noted in a few cases (Meelu et al. 1992b; Diekmann et al. 1993; Kundu et al. 1993), they were rarely translated into differences in rice yields. Similar results were found in comparisons between LGMs of different ages (Bhardwaj and Dev 1985; Nagarajah 1988; Morris et al. 1989; Meelu et al. 1992b; Kolar et al. 1993), even though one might expect decreasing succulence and N content with LGM age to have had an effect on decomposition and rice yields. Perhaps the selected GML species and age were too similar in composition to form significant treatment levels. In contrast, legume plant parts (leaves, stems, roots), which vary significantly in N contents and C:N ratios (Ventura et al. 1987; Palm et al. 1988) showed differences in yield response. John et al. (1989) and Morris et al. (1989) found that GML root material (either alone or in combination with legume tops) contributed very little to rice yield increases because of low N content and wide C:N ratios.

Knowledge about the factors controlling LGM decomposition/N mineralization has led to several recommendations for improving LGM benefits on rice yields. However, management problems still exist which may have a larger impact on the success and adoption of legumes than these decomposition factors. As mentioned earlier, lack of mechanical equipment is a major limitation for many farmers in South Asia. While researchers have looked at optimal depths for incorporating LGMs under experimental conditions (Uppal 1955; Staker 1958), little work has been done on practical and "best management" techniques for incorporating LGMs under farmers' field conditions or mechanical limitations (Palaniappan and Budhar 1994). Research in this area would obviously involve development of low technology implements and methods. Another approach might be to look at the effect of legume growth habit on ease or difficulty of soil incorporation; plants with short, bushy morphologies might be easier to incorporate than those with tall, pole-like growth habits.

NITROGEN BENEFITS OF GREEN MANURE AND FORAGE LEGUMES

The vast majority of research on direct effects from GMIs has concentrated on N contributions. Morris et al. (1989) showed that regardless of various compositional factors such as legume species, age, or plant parts, the quantity of N added by LGMs was the biggest factor determining rice grain yield responses. The most common method for expressing N benefits from GMLs is the Nitrogen Fertilizer Equivalent (NFE) or the quantity of fertilizer N that must be applied to obtain grain yields equal to those obtained with green manure alone. This indirect measurement can best be regarded as an approximation of the direct effect from green manures, because of the assumption that yield responses are only due to the N contribution. Generally NFE values obtained with GMLs and rice range from 34 kg N ha^{-1} to 220 kg N ha"^{1} but average 50-100 kg N ha^{-1} (Meelu and Morris 1988; Buresh and DeDatta 1991; Yadvinder-Singh et al. 1991) (Table 4). Ladha et al. (1996) found that rice following forage legumes yields the same as rice with 24-50 kg fertilizer N ha^{-1}; while Carangal et al. (1994) reported fertilizer substitutions of 50 kg ha^{-1} to greater than 90 kg ha"^{1} of fertilizer N. Obviously some of the variation in NFE from both legume types reflects differences in N additions, but agronomic efficiency and N recovery are also important factors.

Agronomic N-use efficiency is defined as the increase in crop yield per unit of N applied (Cooke 1987) and ties together plant management and environmental factors at the crop level. While agronomic efficiencies vary considerably from experiment to experiment because of differences in management, soils, climate, and cultivars, pooled data indicate that agronomic efficiencies of LGMs are generally similar or slightly greater than those for urea fertilizer (Becker et al. 1995). However, under differing environmental conditions such as hydrology and soil texture, LGMs seem to have more distinct advantages. Using data from the literature, Garrity and Becker (1994) found higher agronomic efficiencies on irrigated rice relative to rainfed rice when urea was the fertilizer; however, N efficiencies with LGMs were similar under the two hydrology regimes. Likewise, N-use efficiency declined quite sharply as soil texture graded from clay to sand in urea fertilizer experiments; whereas the response was much more robust for the LGM treatments. Thus LGMs have a comparative advantage over fertilizer N sources in a wider range of environmental conditions. Further work should concentrate on optimizing LGM use in those niches which give the farmer the greatest flexibility and potential for success.

Evaluation of N recovery from LGMs depends somewhat on the methodology employed. Ladha et al. (1996) estimated recovery of forage legume N by the difference method at 15-31%. Both apparent N recovery (or difference) and ^{15}N methods were used by Yadvinder-Singh et al. (1991) to compare N recoveries of LGM versus chemical fertilizer from several studies reported in the literature. While values ranged from 25% to 58%, due to soil, climate, and management variation, apparent N recoveries from LGM

Table 4: Nitrogen fertilizer equivalence (NFE) of green manures in rice.

Legume	Age (days)	N content (kg ha^{-1})	NFE (kg ha^{-1})	Reference
Aeschynomene afraspera/ A. nitotica	49	-	>100	Alazard and Becker (1987)
Cowpea	-	3.6 (D)[1]	80	Zaman (1983)
Cowpea	-	55-80	98	Yadvinder-Singh et al. (1990)
Cowpea	60	68	60	John et al. (1992)
Milk vetch	60	90	90	Jiao et al. (1986)
Mung bean/cowpea	40-45	74-86	80	Morris et al. (1986)
Sesbania aculeata	-	23	34	Vachhani and Murty (1964)
S. aculeata	67	-	80	Dargan et al. (1975)
S. aculeata	60	104	120	Beri and Meelu (1981)
S. aculeata	50	57	50	Bhardwaj et al. (1981)
S. aculeata	45	109	123	Ghai et al. (1988)
S. aculeata	60	-	90	Shukla et al. (1989)
S. aculeata	-	45-75	72	Yadvinder-Singh et al. (1990)
S. aculeata	-	97-150	136	Yadvinder-Singh et al. (1990)
S. cannabina	-	-	50	Pandey (1983)
S. cannabina	45-65	98-147	100-120	Bhardwaj and Dev (1985)
S. cannabina/S. rostrata	60	10 (F)[1]	80	Bhattarai and Maskey (1996)
S. rostrata	52		130	Rinaudo et al. (1983)
S. rostrata	55	131	80	Crozat and Sangchyosawat (1985)
S. rostrata	50	-	70	Ventura et al. (1987)
S. rostrata	60	161-227	220	Buresh et al. (1993)
S. rostrata	45	45-83	97	Buresh et al. (1993)
S. sesban	84	83	96	Palm et al. (1988)
Sesbania/cowpea/ Sunn hemp	60	108-113	120	Beri et al. (1989a)
Sunn hemp	105	-	100	Ten Have (1959)
Sunn hemp	50	78	75	Bhardwaj et al. (1981)
Sunn hemp	40-60	-	120	Kolar and Grewal (1988)
Sunn hemp	-	41-70	72	Yadvinder-Singh et al. (1990)
Sunn hemp	-	121	148	Yadvinder-Singh et al. (1990)

[1]D = Dry weight (t ha^{-1}); F = Fresh weight (t ha^{-1}).

treatments were similar to or slightly higher than those with fertilizer. On the other hand ^{15}N recoveries for LGMs were less than the fertilizer treatments by as much as 23%. Disparity between these two methods is common, with plant N recovery estimates being generally lower with the ^{15}N method than those obtained by the difference method (Westerman and Kurtz 1973; Vlek and Fillery 1984).

An explanation for these differences was initially proposed by Jansson in 1958. He postulated that biological interchange between N and soil micro-organisms was a significant factor controlling ^{15}N recovery. The mechanism for this interchange was mmeralization-immobilization turnover (MIT), the continuous circulation of N through the mineralization and immobilization activities of heterotrophic soil micro-organisms. Nitrogen cycling would be responsible for immobilizing ^{15}N and mineralizing unlabeled soil N at the same time. Thus the enrichment of an inorganic N pool would be lowered without changing the overall size of the pool. As a result, crops would recover more unlabeled soil N than would be measured by apparent N recovery. Various environmental conditions affect the extent of MIT processes, including additions of high energy, carbonaceous materials (e.g., green manures, crop residues) which stimulate microbial activity and enhance MIT effects (Jansson 1971; Lauren 1991). Thus low crop ^{15}N recoveries may have more to do with conditions that stimulate microbial N cycling or influence interactions between added and microbial N rather than inefficient uptake or utilization of applied N. For this reason many workers have discouraged the use of ^{15}N in the evaluation of fertilizer recovery (Jansson and Persson 1982; Jenkinson et al. 1985; Hart et al. 1986; Diekmann et al. 1993). However, this warning has largely been ignored as many experiments continue to use ^{15}N to assess N-use efficiency.

Nitrogen loss is another factor of importance when assessing the direct effects of LGMs. Generally N losses appear to be higher from urea sources (average 35%) than from green manures (average 14%) (DeDatta and Buresh 1989; Buresh and DeDatta 1991; Becker et al. 1995). However, these evaluations are also made with ^{15}N and thus are subject to the same interpretation problems as for N recovery. Isotopic exchange processes lead to an underestimation of N losses from both fertilizer and LGM N. Isotopic exchange will be enhanced with C rich LGMs; and consequently fertilizer treatments will appear to lose more ^{15}N than LGM treatments. While it is possible that LGMs act as slow release N sources that are more synchronous with rice N uptake and less prone to loss than fertilizer N sources (Becker et al. 1994a), green manure mineralization is very rapid in flooded tropical soils and good management, e.g., immediate incorporation before or after initial soil flooding, is essential to avoid gaseous losses (Beri et al. 1989b; Buresh and DeDatta 1991). Further research without ^{15}N will be necessary to delineate the true loss differences, if any, between LGM and fertilizer N sources.

NON-NITROGEN BENEFITS OF GREEN MANURE AND FORAGE LEGUMES

Finally, the research record for LGMs gives the impression that N is the only contributing factor to observed yield responses in rice. Several workers have established clearly that green manures act as more than a replacement for fertilizer N, i.e., green manures can have an effect on the overall yield potential that no amount of fertilizer N can overcome (Dargan et al. 1975; Chatterjee et al. 1979; Tiwari et al. 1980b; Rekhi and Meelu 1983; Beri et al. 1989b). Improvements in soil physical properties (Yaacob and Blair 1981; DeDatta and Hundal 1984; Boparai et al. 1992), increased acquisition and mobility of macronutrients (Zaman 1983; Yadvinder-Singh et al. 1988; Nagarajah et al. 1989; Parveen 1993) and micronutrients (Sniping 1983; Thind and Chahal 1983; BRRI 1985; Mridha 1987; Benbi and Brar 1992), as well as reductions in soilborne pests and pathogens (Reddy et al. 1986; Pariselle and Rinaudo 1988) have all been demonstrated in GML-rice cropping systems. However, many of these reports are site specific or with only one legume species. To better understand the potential for forage legumes and GMLs in rice-based cropping systems, more research is necessary to compare and contrast the various physical, chemical, and biological non-N benefits (and problems) associated with a range of green manure species. Data should be gathered under several soil-climate conditions to determine the extent of the benefits as well as the comparative advantages, if any, of specific legumes.

RESIDUAL EFFECTS FROM FORAGE AND GREEN MANURE LEGUMES

Long-term benefits or true residual effects from GMLs in a second crop after rice are much less dramatic than with the first crop. Perhaps as a result, a comprehensive analysis of residual effects from forage legumes and GMLs is absent in the literature. We undertook an examination of more than 30 documented experiments to evaluate what generalizable trends might be found on residual benefits from GMLs.

In rice-rice rotations, more than half of the surveyed studies recorded no residual effects (Table 5) (Wilson et al. 1980; Gu and Wen 1981; Mo and Qian 1983; Morris et al. 1986; Furoc and Morris 1989; Watanabe et al. 1989; Meelu et al. 1992b), while other studies reported small but significant yield increases (13-43% over controls) in the second crop of rice (Panse et al. 1965; Jha et al. 1980; Rinaudo et al. 1988; Morris et al. 1989; Ventura and Watanabe 1993; Becker et al. 1994a). Reasons for lack of a trend are not clear, but Morris et al. (1989) attributed the results to varied N loss mechanisms.

More definitive residual effects were evident from rice-wheat experiments where significant yield benefits were noted in 15 out of 22 studies (Table 6). Boparai et al. (1992), Kolar et al. (1993), Rekhi and Bajwa (1993), and Gill et al. (1994) found quite low responses of 4-11% over controls, while the bulk of the studies reported intermediate yield increases of 15-38% (Bhardwaj et al. 1981; Gu and Wen 1981; Sharma and Mittra 1988; Chaudhary 1990; Rathore et al. 1995; Sharma et al. 1995). Relatively high residual effects between 54% and 94%> were measured by Tiwari et al. (1980a, 1980b); Mahapatra et al. (1987), Mahapatra and Sharma (1989), and Mann and Ashraf (In press). In addition LGMs contributed to significant increases in wheat N uptake ranging from 4 kg ha^{-1} to 17 kg ha^{-1} (Goswami et al. 1988; Rekhi and Bajwa 1993; Sharma et al. 1995).

Table 5: Residual yield response to green manuring in rice-rice rotations.

Green manure	Applied green manure (kg N ha^{-1})	Residual response relative to control (%)	(kg ha^{-1})	Reference
Azolla	46	NS[1]	-	Watanabe et al. (1989)
Azolla	87	17.0	500	Ventura and Watanabe (1993)
Blue-green algae	2	NS	-	Wilson et al. (1980)
Cowpea	11-75	NS	-	Morris et al. (1986)
Crotalaria	-	13.4	163	Panse et al. (1965)
Ipomoea carnea	135	14.4	580	Jha et al. (1980)
Milk vetch	75	NS	-	Gu and Wen (1981)
Milk vetch	-	NS	-	Mo and Qian (1983)
Mung bean	13-80	NS	-	Morris et al. (1986)
Sesbania	45	15.0	221	Panse et al. (1965)
Sesbania (60 days)	173-224	14.5	300	Meelu et al. (1992b)
Sesbania	73	17.0	500	Ventura and Watanabe (1993)
S. cannabina	122	-	-	Morris et al. (1989)
S. rostrata	-	43.0	990	Rinaudo et al. (1988)
S. rostrata	145	-	600	Morris et al. (1989)
S. rostrata/ S. cannabina	43-219	6.0[2]	-	Furoc and Morris (1989)
Sesbania + rice straw	90	10.0	300	Becker et al. (1994a)

[1]NS = no significant residual effect.

[2]6% of residual nitrogen.

Variability in these responses to LGM additions is most likely due to the quantities of applied N, the quality of the green manure, or methodological differences. In the latter case, some researchers supplemented the wheat crop on LGM and control plots with an additional 40-120 kg fertilizer N ha^{-1} (Kolar et al. 1993; Rekhi and Bajwa 1993; Gill et al. 1994; Sharma et al. 1995). While residual effects were still detectable, the yield responses in these experiments were only 150-500 kg ha^{-1}; whereas in non-N supplemented experiments, responses generally were higher at 440-1000 kg ha^{-1} (Tiwari et al. 1980a, 1980b; Bhardwaj et al. 1981; Gu and Wen 1981; Mahapatra et al. 1987; Sharma and Mittra 1988; Mahapatra and Sharma 1989; Chaudhary 1990; Rathore et al. 1995). It is probable that the additional fertilizer N masked residual LGM effects by diluting the impact of mineralized N from the green manure additions. Indeed, most of the studies with non-significant yield results also might have shown some residual effects had no additional N fertilizer (60-120 kg N ha^{-1}) been applied to the wheat (Goswami et al. 1988; Meelu et al. 1992a; Yadvinder-Singh et al. 1994; Aggarwal et al. 1995). Such methodological differences arise because objectives differ between experiments, and because residual effects are not usually the main focus of the experiments. Future research should be designed with common methodologies and goals relating primarily to the long-term benefits of GMLs.

Table 6: Residual yield response to green manuring in rice-wheat rotations.

Green manure[1]	Applied green manure (kg N ha^{-1})	Residual response relative to control[2] (%)	(kg ha^{-1})	Reference
Azolla	80	4.6	68	Chaudhary (1990)
Azolla + *Sesbania*	60 + 30	46.5	605	Mahapatra et al. (1987)
Azolla + *Sesbania*	40 + 40	63.0	1000	Mahapatra and Sharma (1989)
Blue-green algae	-	17.7[2]	140[2]	Rathore et al. (1995)
Cassia tora	-	NS[3]	-	Ram et al. (1990)
Cowpea	80	34.4	506	Chaudhary (1990)
Cowpea	89	.11.0	483	Kolar et al. (1993)
Crotalaria	78	34.0	656	Bhardwaj et al.(1981)
Crotalaria	97	18.8	240	Sharma and Mittra (1988)
Crotalaria (with added N)	120	23.4	300	Sharma and Mittra (1988)
Crotalaria (with added NP)	149	38.3	49()	Sharma and Mittra (1988)
Crotalaria	100	9.9	433	Kolar et al. (1993)
FYM	120	12.3[4]	480[4]	Aggarwal et al. (1995)
Ipomoea carnea	28	17.0	324	Bhardwaj et al. (1981)
Milk vetch	75	25.9	280	Gu and Wen (1981)
Mung bean	80	41.2	607	Chaudhary (1990)
Mung bean residues	64	16.9	550	Sharma et al. (1995)
Sesbania	15	60.3	570	Tiwari et al. (1980b)
Sesbania	18	54.1	647	Tiwari et al. (1980a)
Sesbania	57	27.0	529	Bhardwaj et al. (1981)
Sesbania	-	NS	-	Bhatti et al. (1985)
Sesbania	-	NS	-	Goswami et al. (1988)
Sesbania	80	11.2	L65	Chaudhary (1990)
Sesbania	L16	8.0	290	Boparai et al. (1992)
Sesbania	84	NS	-	Meelu et al. (1992a)
Sesbania	84	8.4	367	Kolar et al. (1993)
Sesbania	114	4.2	150	Rekhi and Bajwa (1993)
Sesbania	-	6.9	275	Gill et al. (1994)
Sesbania	104	NS	-	Yadvinder-Singh et al. (1994)
Sesbania	140	NS	-	Aggarwal et al. (1995)
Sesbania	73	15.4	500	Sharma et al. (1995)
Sesbania	-	94.2	1650	Mann and Ashraf (In press)
Sesbania + FYM	104 + 89	13.9[4]	550[4]	Yadvinder-Singh et al. (1994)
Sesbania rostrata	80	37.1	546	Chaudhary (1990)

[1]N = nitrogen; P = phosphorus; FYM = farmyard manure.
[2]After 2nd year.
[3]NS = no significant residual effects.
[4]After 3rd year.

Another possibility for differing residual effect responses found amongst rice-wheat experiments relates to the quantity of N applied. It should be noted that sometimes the biomass or N content of a GML is not reported making it difficult to generalize about the impact of the additions (Tiwari et al. 1980a, 1980b; Ram et al. 1990; Gill et al. 1994; Rathore et al. 1995). However, even when such data are available (or estimated), there is no clear relationship between pooled residual responses and N added as LGM (Fig. 1). Lack of a relationship is most likely caused by soil fertility differences between sites, reflecting differing N mineralization potentials amongst soils (Nagarajah 1988; Becker et al. 1994b). Also LGM-N additions from the surveyed experiments (70-100 kg N ha^{-1}) probably do not represent enough of a range to delineate a trend. For example, Sharma and Mittra (1988), with a range of 97-149 kg N ha^{-1} of applied LGM, demonstrated a linear residual response in wheat yields (Fig. 2). These observations indicate the need for coupling measures of residual effects with site soil fertility (e.g., N mineralization potential); for running experiments on more soil types (e.g., farmers' fields rather than research plots); and for applying a wider range of LGM-N to elucidate controls on residual effect responses.

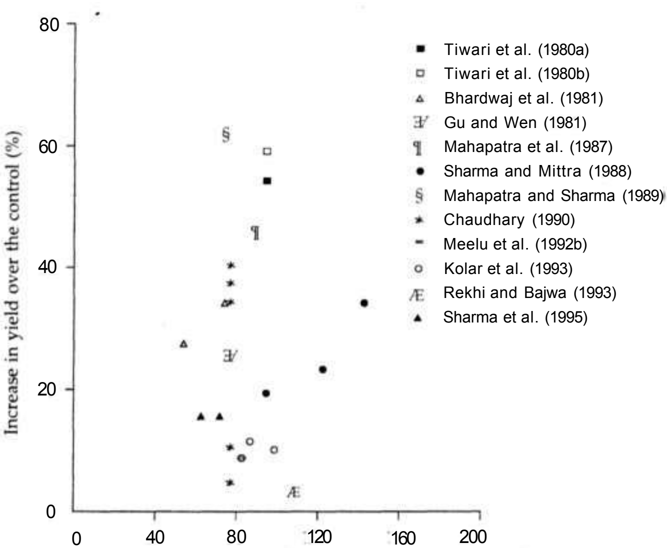

Figure 1: Relationship between pooled residual responses and legume green manure (LGM) nitrogen (N) levels.

Only three of the surveyed GML-rice-wheat experiments recorded N uptake data for both crops (Goswami et al. 1988; Rekhi and Bajwa 1993; Sharma et al. 1995), but by collecting N uptake data in both the first and second crops following a GML, one can determine the relationship between added

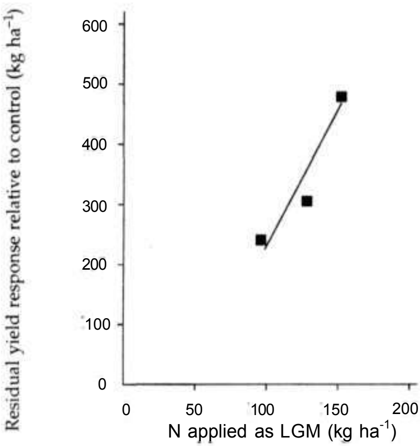

Figure 2: Residual yield response as a function of legume green manure (LGM) nitrogen (N) level.
(Source: Sharma and Mittra 1988)

residual N (LGM N added minus net rice N uptake from LGM treatment) and residual N benefits (wheat N uptake in GML treatment minus wheat N uptake in control). This approach assumes that residual responses are largely dependent on the LGM-N remaining after the first rice crop. Efforts to enhance N_2 fixation levels of >100 kg N ha^{-1} appear to have limited utility on the first rice crop (Furoc and Morris 1989; Yadvinder-Singh et al. 1991). But assuming few. losses of added LGM-N, what might the residual effects be from N application levels greater than 100 kg N ha^{-1}?

The chemical composition or quality of a LGM is also an important factor when evaluating residual effect responses, yet few experiments explore the role of composition on long-term effects. An excellent review paper by Bouldin (1988) associates the direct benefit of a LGM with a rapidly decomposing pool and the residual effect with a much slower decomposing pool which partially explains the low residual effects observed by researchers. Using Bouldin's hypothesis, Becker et al. (1994a) suggested that the magnitude of a residual response may relate to N persistence as determined by the lignin-to-N ratio of a LGM. In contrast, Shi et al. (1981) attributed the higher residual N availability and yield response from milk vetch *(Astragalus glycyphyllus)* compared to *Azolla* to the lower lignin content in the milk vetch relative to the *Azolla.* Clearly, additional research is necessary to determine what LGM quality factors control decomposition and how they relate to residual effects.

In the surveyed literature, residual effects were commonly observed within the initial cycle of GML-rice-wheat. BRRI (1986) reported that residual effects from cowpea and *Sesbania* green manures persisted for more than three cropping cycles. In two cases, however, GML benefits were only observed after the second (Rathore et al. 1995) and third years (Yadvinder-Singh et al. 1994). While Aggarwal et al. (1995) found no residual effects from GMLs after 6 years, they did measure a benefit from the second year onwards with farmyard manure (FYM). These cases lend support to another hypothesis by Bouldin (1988) that residual effects can be increased with continued use of GMLs (10 years) through cumulative additions to the "slow" mineralizable N pool (labile soil organic N). With the exception of work by Yadvinder-Singh et al. (1994) and Aggarwal et al. (1995), no experiments measuring residual benefits from GMLs were more than 2-3 years. In some cases significant yield increases in wheat were associated with increases in soil organic C and/or N (Mahapatra et al. 1987; Sharma and Mittra 1988; Meelu et al. 1992b; Kolar et al. 1993; Rathore et al. 1995). However, given that it is the labile fraction of soil organic matter that is being influenced by LGM additions and that this is generally a small and highly variable fraction of the total pool, measurements of total C and N may not be very useful for monitoring biologically meaningful changes in mineralizable C and N pools over prolonged periods. Measurements of the more labile N pools (microbial biomass N, potentially mineralizable N, active soil N) should accompany experiments of long duration as a test of Bouldin's hypothesis.

When ^{15}N methods are utilized for evaluating residual effects, benefits range from 2.9% to 14% of the originally applied N (Wilson et al. 1980; Mo and Qian 1983; Goswami et al. 1988; Huang and Broadbent 1989; Watanabe et al. 1989; Rekhi and Bajwa 1993). These results agree in principle with those from non-isotopic experiments (that residual effects from GMLs are generally small). However, the ^{15}N approach undoubtedly underestimates the actual magnitude of long-term effects because of the N isotopic exchange processes mentioned earlier in this chapter. Residual ^{15}N upon reaching isotopic equilibrium with soil microbial and available N pools will appear to be slowly mineralizable because the mineralized N fraction will have a much lower ^{15}N enrichment than that of the original fertilizer N. This discussion does not dispute the concept that residual fractions of LGM-N may be relatively inaccessible or slowly decomposible making residual effects rather small. However, it does argue that ^{15}N results definitely under-represent the magnitude of whatever residual effect exists.

Unfortunately little research has addressed the residual effects of forage GMLs in rice-based cropping systems. Work by Meelu and Rekhi (1981), De et al. (1983), Tengco et al. (1989), Carangal et al. (1994), and Ladha et al. (1996) has assessed the more immediate effects of these legumes in enhancing farm productivity through fodder and rice yields. In addition to determining the actual residual effects of forage GMLs, future research should also focus on such questions as: How much do residual effects from forage GMLs add to overall farm productivity? Over a range of environmental conditions, what are the N contents and biomass of forage GMLs after the last cutting? How do the number of forage cuttings affect direct and residual effects? What are the N mineralization patterns of various forage GMLs after the last cutting? Is there an effect of age on decomposition and subsequent direct and residual effects? What is the contribution of forage legume root biomass to direct and residual effects and in comparison to roots from GMLs?

Finally, non-N benefits from LGMs have generally been viewed as direct effects with little attention to persistence of the benefit. Boparai et al. (1992) found increases in soil aggregate stability and lower bulk densities after three years of *Sesbania-rice-wheat.* Residual yield effects in wheat were attributed to these improved physical properties, but additional data would be necessary to determine the duration of these effects. Knowledge of the long-term effects on non-N parameters is essential for sustaining productivity in GML-rice cropping systems. Research on non-N benefits should also address cropping systems constraints to realizing these benefits. For example, puddling soil in a rice-wheat system effectively prevents any long-term improvement in soil aggregation that would benefit wheat.

CONCLUSIONS

Liebig's Law of the Minimum has dictated the research emphasis on N contributions from GMLs in rice-based cropping systems. This effort has led to achievements such as identification of legume species with good green manuring potential (e.g., high N content); and understanding control on green manure mineralization/decomposition as well as N transformations in flooded soils. Because of problems with ^{15}N methodologies, some additional work is needed to better compare and contrast plant recoveries and system losses from LGMs versus N fertilizers.

Many workers have noted that direct effects from LGMs are not solely due to N contributions. Assuming that N is not a yield-limiting factor, LGMs have also been observed to significantly increase the yield potential of rice. Several factors have been identified to explain these increases in yield potential, but systematic research to determine the non-N benefits from a range of forage legumes and GMLs and over a range of soil and climate resources is sorely lacking. Such research efforts will require agronomists, soil scientists, plant pathologists, and plant breeders to work together in a more multidisciplinary fashion than in the past. The result of such investigations should ultimately provide farmers with a set of broad principles, an appropriate knowledge base, and the capability to adapt to changing market demands and opportunities, while maintaining a sustainable resource base.

Management constraints, which limit the feasibility and cost effectiveness of GMLs, will continue to outweigh the benefits associated with legumes as long as legumes (grain, forage, and green manure) are advocated (and studied) only as alternative N sources. This situation is likely to persist even if the cost of inorganic N fertilizer increases in the near future due to the removal of government subsidies. Broadening the knowledge base regarding non-N benefits is essential for promoting legumes in rice-based cropping systems as a sustainable agricultural practice to regenerate depleted soil resources and boost declining yields.

A comprehensive analysis of residual effects from GMLs in rice-based systems determined no clear trends in rice-rice systems, but significant residual effects of 68-1000 kg grain ha^{-1} were found in a majority of rice-wheat studies. While annual residual benefits are generally small, cumulative effects from continued use of GMLs contribute to restoring degraded soils and increased soil productivity. Even so, past research on GMLs in rice-based cropping systems has concentrated on the direct effects of GMLs. Consequently residual effect data are often incomplete, not long term enough or focused. Clearly, research is required which specifically targets the extent and control on residual benefits from forage legumes and GMLs in rice-based cropping systems.

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5

Factors Affecting Biological Nitrogen Fixation and Residual Effects of Legumes in the Indo-Gangetic Plain

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ABSTRACT

Statistical information suggests a substantial increase in area under irrigation, under rice and wheat, and in use of chemical fertilizers in Asia. However, a slowing down in growth of productivity of rice and wheat has been reported in recent times. In the past, legumes occupied a significant area in the Indo-Gangetic Plain (IGP) but the area has declined due to the more remunerative and relatively more stable cereals. However, legumes still have a potential role in sustaining productivity of rice- and wheat-based systems. Atmospheric nitrogen (N) fixed by legumes in symbiosis with root nodule bacteria potentially meets much of the N demand of the legume and can contribute to the N requirements of subsequent crops. This aspect and the factors affecting biological nitrogen fixation (BNF) by legumes have been reviewed. Data specifically from IGP have been very scanty and substantial information has been drawn, particularly on the factors (temperature, moisture, salinity, host plant, and rhizobia) affecting BNF and residual effects of legumes, from other sources.

Indiscriminate use of nitrogenous fertilizers has resulted in increased mineral-N concentration in soils of IGP, at least in some areas. These concentrations are suppressive for BNF by legumes. Such changes in the micro-environment in soils of IGP will require identification of appropriate legumes and cultivars that yield well and fix adequate N under the changed environments. Experiments to assess the scope of sustaining productivity of rice- and wheat-based cropping systems through increased harnessing of BNF by legumes have been proposed.

In 1996 Asia produced 91% of the world's rice *(Onyza sativa) and* 43% of the world's wheat *(Triticwn aestivum),* amounting to 572 million t rice and 261 million t wheat (FAO 1997). The growthrate of the population in Asia of 3 billion is about 2% per annum, and an ever increasing production (>2.5% per annum) of these staple grains will be needed. This is imposing an inevitable threat to the natural resource base, even in traditionally well-endowed areas, and examples of adverse consequences of continuous cereal cropping are being increasingly documented (Singh and Paroda 1995). A closer

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examination of cropping sequences is needed if productivity of rice and wheat is to be maintained and further increased. In this context, the well-known ameliorative effects of legumes in crop rotations need close attention in relation to the sustainability of rice and wheat production systems. Sustainable agriculture involves the successful management of agricultural resources to satisfy changing human needs while maintaining or enhancing the natural resource base and avoiding environmental degradation (CGIAR/TAC 1988). It relies greatly on renewable resources such as biologically fixed nitrogen. Biological nitrogen fixation (BNF) helps in maintaining and/or improving soil fertility by using nitrogen (N) which is in abundance in the atmosphere. Intensive agricultural systems such as rice-wheat in the Indo-Gangetic Plain (IGP) are characteristically expanded nutrient cycles involving the export of crops from a farm and require continued imports of nutrients to the farm.

Nitrogen is one of the most limiting nutrient for increasing crop productivity. Input efficiency of N fertilizer is low (Prasad et al. 1990; Singh and Paroda 1995; Abrol et al. 1997) and in turn it contributes substantially to environmental pollution. The BNF by legumes offers an economically attractive and ecologically sound means of reducing external N inputs and improving the quality and quantity of internal resources. However, mere inclusion of legumes does not guarantee increased contributions of N and other benefits to the soil/cropping system as legume crop growth and BNF are influenced by a number of physical, environmental, nutritional, and biological factors. In this chapter, factors affecting BNF by legumes and residual effects of legumes on succeeding crops, with particular emphasis on chickpea *(Cicer arietinum),* pigeonpea *(Cajanus cajan),* and groundnut *(Arachis hypogaea)* are reviewed. Although the factors affecting BNF by legumes are largely known, the present review was prepared mainly for the benefit of those interested in improving the beneficial effects of legumes in rice and/or wheat cropping systems. A literature search (1975-97) on these aspects with particular reference to rice-wheat cropping system in IGP gave very little direct information and so we have attempted to extrapolate findings from other systems as well.

CHARACTERIZING RICE-WHEAT AREAS FOR LEGUMES

The increase in world irrigated area during 1961 and 1994 was 116.7 million ha of which 63% was in Asia (i.e., 74 million ha of the total 164 million ha in Asia) (Table 1). This increase is largely the result of canal and tubewell irrigation projects. Rice and/or wheat are preferred cereals on irrigated lands in Asia. It is widely observed that legumes are generally grown as rainfed crops and are rarely irrigated even if this facility is available. Also, whenever a rainfed area receives an irrigation facility legumes are largely replaced by input (mainly fertilizer and water) responsive cereals such as rice, wheat, and maize *(Zea mays).* The area under legumes [pulses + soybean

Table 1: Agricultural area and production and consumption of nitrogenous fertilizers of cereals and legumes.

Year	Area (million ha)		Total harvest area (million ha)				Nitrogenous fertilizers (million t)	
	Total agriculture	Irrigated	Rice	Wheat	Pulses	Soybean	Production	Consumption
1961								
Asia	1052.8	90.2	107.0	61.2	38.8	11.6	1.7	2.1
World	4486.8	138.8	115.5	203.9	63.7	23.8	12.9	11.6
1971								
Asia	1102.6	111.4	122.7	70.0	34.0	9.3	6.4	8.0
World	4610.4	171.1	134.7	213.0	63.1	30.0	38.4	33.5
1981								
Asia	1159.6	133.9	129.4	79.8	34.4	10.3	19.4	21.7
World	4719.8	222.5	145.3	239.2	62.0	50.5	62.3	60.5
1991								
Asia	1265.1	156.7	131.7	87.3	35.7	12.8	32.3	37.9
World	4855.1	245.8	146.7	223.2	68.6	55.0	80.6	75.5
1997								
Asia	1264.5 (1994)[1]	164.2 (1994)	135.2	102.5	39.2	16.2	39.9 (1995)	44.9 (1995)
World	4872.7 (1994)	255.5 (1994)	150.8	229.2	71.8	67.2	86.7 (1995)	78.7 (1995)

[1] Figures in parantheses represent the year.

Source: FAO (1997).

(Glycine max)] and major cereals (rice + wheat) during 1961 to 1997 has increased, both in Asia (by 10%, i.e., 55.4 million ha under legumes and by 41%, i.e., 237.7 million ha under cereals) and the world (by 59%, i.e., 139 million ha under legumes and by 19%, i.e., 380 million ha under major cereals) (Table 1). Therefore, it is interpreted that legumes have been shifted to new lands or cropping systems where these were not grown previously. In 1961/62, Punjab (including present states of Haryana and Himachal Pradesh in India) had 3.4 million ha under irrigation and 2.46 million ha under legumes. In 1990/91 irrigated area increased to 6.6 million ha whereas area under legumes decreased to 0.95 million ha (78%) (Table 2). During the same period, in Madhya Pradesh state of India, the area under grain legumes increased by 16.7% by introduction and spread of a new legume, soybean, on an area of 2.6 million ha (Table 2). Irrigated area in Madhya Pradesh also increased from 1.1 million ha in 1964/65 to 4.3 million ha in 1990/91. Both the states also registered a significant increase in area under both rice (22% in Madhya Pradesh, 5.3 times in Punjab) and wheat (12% in Madhya Pradesh and 1.4 times in Punjab). The extent of increase was greater in Punjab (northwestern IGP) than in Madhya Pradesh (non-IGP area). Bihar (another IGP area) also witnessed a significant reduction (47%) in the area

under pulses during 1964/65 to 1990/91. During the same period the area under pulses in India showed a marginal increase of 0.3 million ha (from 24.2 million ha to 24.5 million ha). This further suggests the trend in legume area shifts from IGP to non-IGP areas in India. A similar scenario appears to be the case for Bangladesh, Nepal, and Pakistan (data presented at a workshop on Legumes in rice-wheat cropping systems of the Indo-Gangetic Plain: Constraints and opportunities, 15-17 Oct. 1997, ICRISAT, Patancheru, India).

Table 2: Changes in area ('000 ha) from 1961/62 to 1991/92 under rice, wheat, pulses and soybean in Punjab[1] and Madhya Pradesh, India.

	Crop				Irrigated area		
Year/State	Rice	Wheat	Pulses	Soybean[2]	Rice	Wheat	Pulses
1961/62[3]					1964/65[4]		
Punjab	446.3	2240.4	2459.0	Nil[2]	377.0	1395.8	518.0 (2251.10)[5]
Madhya Pradesh	4193.8	3176.5	3879.1	7.7	547.2	240.8	72.9 (3914.6)
1991/92[6]					1990/91[7]		
Punjab	2819.9	5419.1	525.4	0.6[2]	2701.8	5014.1	271.0 (931.3)
Madhya Pradesh	5131.5	3547.0	4528.4	2648.8	1019.3	2014.0	586.0 (5008.6)

[1] Includes present states of Haryana and Himachal Pradesh that were formed after 1961/62.

[2] Soybean statistics for Punjab are available for 1971/72 and were not available for previous years. In 1991/92 the crop area was reported for Himachal Pradesh only and it is interpreted that the other states did not have measurable area under soybean.

[3] Government of India (1970).

[4] Government of India (1971).

[5] Values in parentheses refer to total area (irrigated + nonirrigated) under pulses.

[6] Government of India (1993).

[7] Government of India (1994).

In most legumes studied, BNF is suppressed by high levels of mineral N in the soil (Streeter 1988). Soil mineral-N levels of 20-89 mg N kg^{-1} soil have been found to suppress BNF traits by about half in several legumes (Rupela and Johansen 1995b). It is widely believed that N once applied is either used up by the receiving crop or is lost and much of it does not stay in profile. But we recorded increases in soil N level at sowing of chickpea due to the application of increasing N fertilizer levels to the preceding sorghum on a Vertisol (Table 3). The increased soil N levels suppressed BNF by chickpea. It is therefore likely that the N applied to rice and wheat [N-use efficiency is reported to be in the range of 30-35% (Abrol et al. 1997)] is available to the succeeding crops in different soils of the IGP. Mean available soil N level (alkaline permanganate method) measured in farmers' fields growing rice-wheat regularly in Punjab, was 22-224 mg N kg^{-1} soil (Table 4). Thus legumes grown in irrigated rice-wheat areas may face suppressive levels of soil mineral N.

Table 3: Total nitrogen (N) and mineral-N in top 15 cm of a Vertisol at the time of sowing chickpea, 1990-95, ICRISAT, Patancheru, India.

N-application	Total N[1] (mg kg^{-1} soil)			Mineral N (mg kg^{-1} soil)		
to preceding sorghum[2]	Nodulated chickpea	Nonnodulated chickpea	Mean	Nodulated chickpea	Nonnodulated chickpea	Mean
N1	561	517	531	16	14	10
N2	549	527	535	18	15	13
N3	636	544	583	22	23	18
N4	617	583	589	26	27	26
SE	± 12.8 (17.2)[3]		± 4.0	±2.5(1.4)[3]		±2.3

[1]The data for total N are based on four and not five years.

[2]Nodulated and nonnodulated chickpea were subplots and four N levels NI, N2, N3, and N4 were the main plots for five years (1990/91 to 1994/95). No N was applied to chickpea. Preceding sorghum (rainy season) received 0 (NI), 40 (N2), 80 (N3), and 160 (N4) kg N ha^{-1} (in two split) doses in all the five years, except in 1992 when 0 (NI), 80 (N2), 160 (N3), and 320 (N4) kg N ha^{-1} was applied. Twenty kg P ha^{-1} as single super phosphate was applied to chickpea at sowing in 1990/91, 1992/93, and 1994/95. Data are from non replicated demonstration plots (8 m x 7.2 m); year was used as replication for statistical analysis.

[3]SE to compare means within an N-level.

Table 4: Available nitrogen (N) concentration in soil in farmers' rice-wheat fields in Punjab, India.

Available N (mg kg^{-1} soil)[1]		Before sowing	
Mean (n)[2]	Range	of crop (year)	Reference
96 (23)	38-224	NA[3]	Grewal and Kanwar (1967)
67 (7)	22-106	Wheat (1976/77)	Dhillon et al. (1978)
61 (5)	50-67	Rice (NA)	Chand et al. (1984)
65 (20)[4]	36-150	Rice (NA)	Gupta et al. (1988)

[1]Available N concentration by the alkaline permanganate method of Subbiah and Asija (1956). In the references of Dhillon et al. (1978) and Chand et al. (1984), data was available as kg N ha^{-1} in surface (15-20 cm) soil. Concentration of N was calculated assuming that one ha of top 15 cm soil weighs 2242760 kg.

[2]n = number of farmers' fields observed is given in parentheses.

[3]NA = information not available.

[4]Mineral-N concentration by the method of Bremner (1965) for the same samples was 27.3 (range 8-46) mg kg^{-1} soil.

With assured water input, nitrogenous fertilizer use has increased over the years. Global production of nitrogenous fertilizers has increased from

12.9 million t in 1961 to 86.7 million t in 1995 (a 5.7-fold increase over 1961) (Table 1). In 1995, Asia consumed 44.9 million t of nitrogenous fertilizers while it produced only 39.9 million t. Since 1961, Asia has been an importer of at least 5 million t nitrogenous fertilizers annually. Subsidies on agricultural inputs (including fertilizers) available in many countries would have significantly contributed to enhancing their use even by small farmers. In a survey in 1996 it was noted that of the 231 farmers interviewed in Punjab (India), 66% area cultivated by them received higher than the recommended dose of N (120 kg N ha^{-1}) for rice and 37% for wheat (Sidhu et al. 1998). Such an application of more than the recommended dose of nitrogenous fertilizer in intensive cropping of rice-wheat system in the states of Haryana and Punjab has resulted in increased nitrate concentrations in groundwater over a 10-year period (Abrol and Gill 1995). Further, such a high use of N annually seems to be making soils unfit for harnessing BNF by legumes. Alternatively, it may need legume varieties whose BNF system can tolerate high concentration of soil N. Biological nitrogen fixation by legumes is beneficial to the system in several ways. It reduces fertilizer costs, runoff, and leaching. The organic N in legume residues acts as slow release N fertilizer to increase N-use efficiency. Legumes also add organic matter besides N. The latter is particularly important as organic matter content is low in IGP.

FACTORS AFFECTING BNF BY LEGUMES

Biological nitrogen fixation can effectively supply N to a legume provided there is no other factor limiting plant growth except N supply (Bohlool et al. 1992). The interaction of *Rhizobium,* host plant, and environment determines the proportion of legume N derived from the atmosphere. Though the determinants of BNF by legumes have been dealt with in other recent papers (Bohlool et al. 1992; George et al. 1992; Peoples and Craswell 1992), the present coverage will be limited to general principles (discussed in the preceding section) that are relevant to legume production in rice- and/or wheat-based cropping systems.

Rhizobium

Indigenous soil rhizobia may not be as effective as inoculant strains; however, they can compete well with introduced strains for nodule formation. *Rhizobium* inoculation in such a situation can result in no apparent benefit in N_2-fixation (Dowling and Broughton 1986). Further, Thies et al. (1991a) reported that a response to inoculation may not be obtained if the number of native effective soil rhizobia exceeds 50 cells g^{-1} soil.

Soil flooding during the rainy (rice-growing) season adversely affects rhizobial numbers. Kumar Rao et al. (1982) observed that the population of cowpea *(Vigna unguiculata)* group rhizobia was very low (<100 g^{-1} soil) in paddy fields. It appears that continuous cultivation of paddy has an adverse effect on their survival because there were more rhizobia in a field under paddy for two years (i.e., two consecutive rainy seasons) than in one under paddy for 6.5 years. Similarly, an approximately 100-fold decrease in chickpea rhizobial density was observed in flooded soil when rice followed chickpea (Rupela et al. 1987). Such a decline in *Rhizobium* numbers may necessitate regular inoculation of chickpea or pigeonpea or other legumes, when they are grown after rice to ensure establishment of effective symbioses Ladha et al. (1989a) reported survival in high numbers of rhizobia of the aquatic legume *Sesbania rostrata* in flooded rice rhizosphere. Rain splash and flooding often promote stem nodulation by *S. rostrata;* however, stem inoculation is probably beneficial under dry conditions (Ladha et al. 1992). However, there is little information on the status of native *Rhizobium* populations in soils of the rice-wheat cropping systems of IGP. Such information is required to predict likely responses to *Rhizobium* inoculation. Thies et al. (1991b) developed a model that could predict inoculation requirements of legumes for various environments based on native soil rhizobia and soil N mineralization potential. The model input variables can be obtained through soil analysis before planting of the legume.

Average nodulation (rating '3' on a '1' to '5' scale) of chickpea (Rupela 1990) after paddy has been observed in Bangladesh and Myanmar. It seems that some rhizobia can acclimatize to paddy conditions and survive in large numbers after paddy (authors' observation during field visits). Identification of such strains of different rhizobia and their use as inoculants for relevant legumes should help enhance BNF by legume(s) in rice-legume cropping systems.

Host legume

The potential BNF capacity of a legume is the aggregate of the per-day deficits in mineral N uptake during the legume growth cycle (George and Singleton 1992). Therefore the higher the N yield potential of a legume for a given growth and soil N supply, the higher would be its proportion and amount of N derived from BNF. Large genotypic variation for BNF traits such as nodule number, nodule mass, and acetylene reductase activity (ARA) has been reported for chickpea (Rupela 1994), groundnut (Nambiar et al. 1988), pigeonpea (Kumar Rao 1990), soybean (Wacek and Brill 1976), and cowpea (Zari et al. 1978). Using ^{15}N isotope-based methods, differences among cultivars have been detected in soybean (Hardarson et al. 1989), groundnut (Giller et al. 1987), mung bean and blackgram (Peoples and Craswell 1992), pigeonpea (J.V.D.K Kumar Rao et al., unpublished), and chickpea (O.P. Rupela, unpublished). However, limited or no efforts have been made to use this variability in breeding for improved BNF in many of these legumes. Intracultivaral variability for nodulation (low, high, and non-nod) was observed in chickpea (Rupela 1994), pigeonpea (Rupela and Johansen 1995a), and groundnut (Venkateswarlu 1997). This is perhaps due to the absence of any natural selection pressure for nodulation or BNF during development of a cultivar allowing the different nodulation types to continue to exist within a cultivar up to release stage. This hypothesis is supported by the fact that during a screening for high nodulating plants at high mineral N in soil, desired plants were observed in 85 out of 90 advanced breeding lines of chickpea (Rupela 1994).

Environment

Temperature

In parts of the tropics the temperature of the surface soil can occasionally reach 65-70°C and at 5 cm depth it is about 50°C (Dudeja and Khurana 1989). The excessive soil temperatures can kill a majority of rhizobia in the surface layers of soil, although some rhizobia can survive for some period at 70° C in dry soil (Marshall 1964). High temperatures can prevent nodulation or can inhibit the activity of N_2-fixation (if nodulation does occur) in legumes. In chickpea, root temperatures of 30°C and above are known to adversely affect the infection and N_2-fixation (Dart et al. 1975; ICRISAT 1983). Chickpea plants exposed to a continuous root temperature of 33°C did not form nodules. Exposure to cycles of favorable and unfavorable temperatures indicated that the nitrogenase activity failed to restart when plant roots were once subjected to 35°C (Dart et al. 1975).

In a glasshouse study at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, root temperature above 30°C resulted in decreased N_2-fixation and poor plant growth. Soil temperature for chickpea roots in pots containing Vertisol with high rhizobial population was maintained by immersing the pots in water baths at 25°C, 30°C, 32°C, and 35°C for eight hours (from 0800 h to 1600 h) a day, for 40 days beginning six days after sowing (ICRISAT 1983). The number of nodules per pot did not differ significantly for the first three temperature regimes, suggesting that the processes involved at the molecular level in the formation of nodules were not affected adversely. However, nodule mass, ARA, and plant growth were significantly reduced at 35°C.

In pigeonpea, it was found that nodulated roots incubated at 26°C gave a higher ARA than nodulated roots incubated at either 20°C or 38°C (Kumar Rao 1990). Eaglesham and Ayanaba (1984) reported the possibility of selecting high temperature tolerant *Rhizobium* isolates that could retain their effectiveness in N_2-fixation in symbiosis with cowpea when the day temperatures were kept above 40°C.

An analysis of the potential areas in IGP for including legumes in rice- and wheat-based cropping systems may indicate the temperature regimes (both favorable and unfavorable) for growing legumes. From such data it would be possible to assess the need for selecting *legume-Rhizobium* symbioses adapted to unfavorable temperatures.

Moisture

Because legumes are generally grown either rainfed or on residual soil water, both water deficit and waterlogging (sometimes) are important factors which influence total legume N derived from fixation. Soil moisture deficiency has a pronounced effect on N_2-fixation because nodule initiation, nodule growth, and nodule activity are all more sensitive to water stress than are general root and shoot metabolism (Gallacher and Sprent 1978; Weisz et al. 1985; Rupela and Saxena 1987; Kirda et al. 1989; Kumar Rao 1990; Nambiar 1990).

Excess soil moisture may also restrict N_2-fixation by reducing the supply of oxygen to nodulated roots or indirectly by reducing availability of photosynthates. Waterlogging in pigeonpea significantly reduced root activity, nodulation, and nitrogenase activity (Matsunaga et al. 1996). It also resulted in root sloughing. With the return of favorable soil moisture conditions (after waterlogging), the surviving plants established new roots that hosted abundant nodules.

Post-rainy season legumes such as chickpea, generally sown on residual soil moisture after the rainy season crop (rice in the IGP), may face water deficit conditions. Rupela and Khurana (1997) reported that soil moisture needed for good nodulation was slightly more than that for good emergence (19%) on a Vertisol. In examining the reason of inoculation failure it was apparent that chickpea had no problem of emergence but failed to form nodules even when an abundant rhizobial population was present. Thus poor nodulation reported on farmers' fields by several researchers may not be due to lack of rhizobia but may be due to sub-optimal soil moisture conditions.

Salinity

Salinity is an emerging constraint to sustained rice and wheat productivity and profitability (FAO 1993). Salinity and sodicity in irrigation water are indeed an increasing problem in Pakistan and in northwestern India (Woodhead et al. 1995). Salinity is a natural phenomenon due to accumulation of salts in the top soil caused by using poor quality (salty) water for irrigation or as a result of poorly-managed irrigation. The pH of sodic soils is usually above 8.5 and can result in reduced availability of phosphorus (P), iron (Fe), zinc (Zn), and manganese (Mn) for plant growth.

Among various crop plants tested, legumes have generally been found to be relatively sensitive to soil salinity (Maas and Hoffman 1977) thus making it more difficult to introduce legumes in saline areas of IGP. However, there is considerable variation in degree of resistance across legume species; for example, *Sesbania* spp. shows a high level of resistance (Keating and Fisher 1985). Legumes such as chickpea and lentil *(Lens culinaris)* grown on residual moisture in a post-rainy season, are particularly prone to salinity damage as salts are progressively concentrated in the soil solution and precipitated towards the soil surface as the soil dries out.

It is generally known that rhizobia can tolerate a higher level of salinity than the host legume (Wilson 1970). The process of root hair infection of legumes is particularly sensitive to salinity stress (Sprent 1984) resulting in reduced nodulation of legumes such as pigeonpea (Subba Rao et al. 1990) and soybean (Singleton and Bohlool 1984). Subba Rao et al. (1990) reported variation among *Rhizobium* strains in their ability to nodulate and fix N_2 with pigeonpea under saline conditions and noted the possibility of selecting effective pigeonpea-*Rhizobium* symbioses for saline soils. Nodulation of groundnut is relatively insensitive to salinity (Sprent 1984).

Insect Damage

Damage to plants by pests and diseases will have deleterious effects on plant growth and thus indirectly on N_2-fixation. Specific damage to root nodules is caused by insects in soil. Two insects, *Sitona* spp. and *Rivellia* spp., are known to damage legume nodules (Gibson 1977). In pigeonpea extensive nodule damage by a Dipteran larva *(Rivellia angulata)* in farmer's fields were reported by Sithanantham et al. (1981). It resulted in significant loss in nodule mass, ARA, and seed yield (Kumar Rao and Sithanantham 1989). Sithanantham and Rupela (1986) reported nodule damage by *Metopina* spp. [subsequently identified as *Metopina ciceri* by Disney (1988)] in chickpea. So far, the activity of this insect is generally seen at locations below 20° N latitude in India. Very little information is available on the occurrence of legume nodule damage by insects and its impact on N_2-fixation with particular reference to IGP. Studies are therefore needed to collect this information and assess its importance with reference to legume inputs of fixed N_2 in rice- and wheat-based cropping systems of IGP.

Nutritional Factors

The *legume-Rhizobium* symbioses impose additional nutritional requirements apart from the minerals needed for the plant growth as a whole.

Nitrogen

Significant increases in yield of legumes in response to a basal application of 20-30 kg N ha^{-1} has been reported for several legumes (Tandon 1992). But its effect on nodulation and N_2-fixation has not been reported in those experiments. Reduced nodulation and ARA in chickpea was observed due to the residual effect of N applied to preceding sorghum *(Sorghum bicolor)* (ICRISAT 1994). It seems that the recommendation of the basal N application to legumes was based on yield response and not its effect on BNF; and also perhaps based on experiments conducted in very low-N soils. Soils in the IGP are expected to regularly receive fertilizer N applied to crops preceding legumes and may already be high in N (Table 4). In general high N levels reduce nodulation and N_2-fixation (Table 5). Under such circumstances BNF contribution from the legumes can be improved by managing soil N either through inclusion of appropriate nitrate tolerant high N_2-fixing legume crops or by appropriate management practices. The results in Table 5 also suggest the potential to select appropriate legumes for areas with high soil N without affecting their BNF contribution to the system. For example, 200 kg N ha^{-1} decreased N_2-fixation in groundnut by 19% whereas the reduction in cowpea was 44% (Yoneyama et al. 1990). However, there could be many other overriding factors, e.g., profitability, suitability, and preference for home consumption, that could determine choice of the legume by farmers of the IGP.

Table 5: Effect of nitrogen fertilizer on total N uptake, and the proportion (P-fix) and total amount of N derived from biological nitrogen fixation (BNF).

Crop	Fertilizer N (kg N ha^{-1})	Total N uptake (kg ha^{-1})	P-fix (%)	N from BNF (kg ha^{-1})	Reference
Groundnut	0	196	61	120	Yoneyama et al. (1990)
	100	210	47	99	
	200	243	42	102	
Soybean	0	89	48	43	Yoneyama et al. (1990)
	100	115	24	28	
Cowpea	0	163	77	125	Yoneyama et al. (1990)
	100	138	67	92	
	200	172	33	57	
Chickpea	0	97	81	79	Herridge et al. (1995)
	50	114	59	59	
	100	115	29	25	

A high level of soil mineral N (31.2 µg mineral N g^{-1} soil) at sowing reduced nodulation of chickpea on a Vertisol field by at least 14%, and proportion of fixed N by 63%, compared with that in the control plots (7.3 ug mineral N g^{-1} soil). In a pot trial with Alfisol, application of five levels of fertilizer N up to 200 kg N ha^{-1} equivalent much before sowing was used to simulate a range of soil mineral N concentrations at sowing (Wani et al. 1997). Of the five legume species [pigeonpea, groundnut, cowpea, soybean, and mung bean *(Vigna radiata)]* studied, mean nodule number and nodule mass plant^{-1} in groundnut, soybean, and mung bean were substantially reduced in the presence of a soil mineral N concentration of 31 µg g^{-1} soil compared with a control treatment (no fertilizer) having 23 µg N g^{-1} soil at sowing. Suppression of N_2-fixation was recorded at 43 µg N g^{-1} soil in pigeonpea, and at 66 ug N g^{-1} soil in cowpea. A direct relationship between nitrogenase activity and different soil N pools at sowing and at flowering was observed in pigeonpea, groundnut, cowpea, and soybean (R^2 = 0.56-0.80) but not in mung bean. Based on the available data, it seems that the general recommendation of applying a starter N dose of 20-30 kg ha^{-1} to legumes may not apply to rice-wheat areas.

Other Nutrients

Any factor affecting plant growth is likely to affect N_2-fixation after an effective symbiosis has been established. Nutrition of plants with minerals other than N is one such factor. It is also important because of the additional nutritional requirements of the symbiosis (Robson 1983). In the rice-wheat systems, the nutrient imbalance caused by deficiency of nutrients such as Zn, sulfur(S), Mn, and Fe was perceived as one of the factors responsible for reduced factor productivity of the cereals (FAO 1993). Srivastava et al. (1997) identified boron (B) deficiency [and to some extent molybdenum (Mo) deficiency] as a major cause of flower and pod abortion in chickpea in Chitwan, Nawalparasi, and Makwanpur districts of Nepal (an IGP country). Correcting deficiency of nutrients such as calcium (Ca), cobalt (Co), copper (Cu), Mo, P, and Zn has been shown to increase N_2-fixation. The nutrients Co, Mo, P, Fe, B, and Zn are considered to be directly involved in symbiotic N_2-fixation (O'Hara et al. 1988). In groundnut, fertilization with B, Co, Mo, and Zn in a medium calcareous soil with and without *Rhizobium* inoculation significantly increased nodulation and plant dry matter (Joshi et al. 1987). Application of Co at a rate of 500 mg cobalt nitrate kg"^{1} seed significantly increased pigeonpea grain yield (Raj 1987). Soil application of 0.45 kg Mo ha^{-1} as sodium molybdate significantly increased nodulation and grain yield of pigeonpea (Khurana and Dudeja 1981). In chickpea, soil application of different nutrients, namely, cobalt chloride @ 1 kg ha^{-1} or sodium molybdate @ 1 kg ha^{-1} or zinc sulphate @ 25 kg ha^{-1} were found to increase grain yields compared to control. However, *Rhizobiwn* inoculation along with the application of Co or Mo or Zn was found to increase grain yields significantly over the control (Namdeo and Gupta 1992).

In the real world, it is possible that many physical, chemical, and biological stresses will interact in a single field at the same or different times. Constraints during the legume production phase are very important. Likewise, factors that could influence the survival of rhizobia between cropping seasons may result in subsequent failures of symbiosis. Attempts have been made to estimate the relative importance of different environmental factors using multi-factor models (Woomer et al. 1988). However, it may not always be easy to assign relative importance to various stresses likely to be encountered in the field. But it is certainly important that we should be constantly aware of the complexity of natural environments. In conclusion, stresses such as excessive temperatures and moisture loss from soil can be reduced by improvement of the organic matter content of soils and this will also help to reduce the problems of nutrient availability. Further improvement of the general nutrition of plants for N_2-fixation must rely on better conservation and more efficient use of nutrients within cropping systems. Even then, there will be an inevitable decrease of soil nutrients, as indicated already, and so ultimately, unless we are prepared to accept ever declining yields, these will have to be replenished in the form of organic amendments (e.g., farm-yard manure or crop residues) and inorganic fertilizers.

RESIDUAL EFFECTS OF LEGUMES

Increase in cereal yields following monocropped legumes was 0.5-3 t ha^{-1}, representing 30-350% increase over yields in cereal-cereal cropping sequences

(Peoples and Craswell 1992). The fertilizer N equivalent of the residual effect of preceding legumes [pigeonpea, cowpea, groundnut, mung bean, and black gram *(Vigna mungo)]* on wheat was reported to range from 12 kg ha^{-1} to 68 kg ha^{-1} (Table 6). The fertilizer N replacement value (FRV) or fertilizer N equivalent value refers to the amount of inorganic N required following a non-legume crop to produce another non-legume crop with an equivalent yield to that obtained following a legume. This comparison provides a quantitative estimate of the amount of N that the legume supplies to the non-legume crop. This does not, however, distinguish between BNF and the 'N sparing effect' which results from substitution by legumes of biologically fixed N for soil N. Therefore, FRV methodology overestimates the N contribution of legumes in a crop rotation. The FRV methodology gives variable estimates depending on the test crop used (Blevins et al. 1990). Recently, ^{15}N methodology has been used to measure the residual effects of legumes to circumvent problems with non-isotopic methods (Senaratne and Hardarson 1988; Danso and Papastylianou 1992). The over estimation by FRV methodology is because it confounds the non-N rotation effect with the N contribution (through BNF or N sparing effect), and also this method assumes that use efficiency of fertilizer and legume N is similar.

Table 6: Grain yield response of rice and wheat to previous legume crops relative to a cereal-cereal cropping sequence.

Crop sequence	Increase in cereal yield (t ha^{-1})	Relative increase in yield[1] (%)	N-fertilizer equivalence[2] (kg N ha^{-1})
Legume-rice			
Soybean	0.80	66	NA[3]
Mung bean	0.20	17	NA
Legume-wheat			
Pigeonpea	0.27	21	NA
Black gram	1.26	98	NA
Mung bean	0.65	51	NA
Cowpea	0.74	58	NA
Groundnut sole)	0.75	23	28
Groundnut (intercrop)	0.34	10	12
Mung bean (sole)	1.60	49	68
Mung bean (intercrop)	0.48	15	16
Cowpea (sole)	1.00	30	38
Cowpea (intercrop)	0.38	11	13

[1]Increase in yield of rice or wheat after legumes over that after cereal.

[2]Amount of inorganic nitrogen required after a non-legume crop to produce a yield of another non-legume equivalent to that produced after a legume.

[3]NA = data not available.

Source: Singh and Verma (1985); Bandyopadhyay and De (1986); Chapman and Myers (1987).

Growing legumes in rotation does improve mineral N content in soil as compared with the cultivation of non-legume crops (Rao and Singh 1991; Wani et al. 1995; Ladha et al. 1996) (Table 7); however, it does not fully explain the beneficial effects of legumes on the following crop. The non-N rotational benefit of the legumes towards yield of subsequent crops has been reported by many researchers (Cook 1988; Danso and Papastylianou 1992; Peoples and Craswell 1992).

Table 7: Some examples of the increased levels of soil nitrate detected following legume growth.

Species	Additional soil nitrate ($kg\ N\ ha^{-1}$)[1]	Reference
Chickpea	+ 14	Herridge et al. (1995)
Mung bean	+ 26	Doughton and Mackenzie (1984)
Black gram	+ 38	Doughton and Mackenzie (1984)
Pigeonpea	+ 15	Ladha et al. (1996)
Crotalaria	+ 19	Ladha et al. (1996)
Siratro	+ 26	Ladha et al. (1996)

Calculated as the difference between the levels of soil nitrate after a legume and after a cereal crop or a period of fallow.

Non-N Rotational Effects

If the benefits of crop legumes in rotations cannot be solely explained in terms of the residual fixed N, then what are the sources of the benefits indicated in Table 6? Several factors may be involved, the relative importance of each dictated by the site, season, and crop sequence. Extra yield from a rotation can result from:

- Increased availability of nutrients other than N such as potassium (K), Ca, magnesium (Mg), Zn, S, and Fe through increased soil microbial activity, deep rooting, and root exudates (Kucey et al. 1988; Ladha et al. 1989b; Wani et al. 1991).
- Improvements in soil structure, mainly soil aggregate formation following legumes, such as after three years of alfalfa *(Medicago sativa),* clover *(Trifolium* sp.), and hairy vetch *(Vicia villosa)* mixture (Latif et al. 1992); or improvements in soil water-holding and buffering capacity with incorporation of legume residues (Buresh and De Datta 1991).
- Growth promoting substances in legume residues (Ries et al. 1977).
- Break in pest cycle. Crop rotations break the cycle of cereal pests and diseases, and phytotoxic and allelopathic effects of different crop residues (Francis et al. 1986). Crop rotation is an effective tool against certain pests, but it does not control all pests and diseases. For example, Johansen et al. (1984) reported that black cutworms *(Agrotis ipsilon)* are more of a problem when maize is rotated with either soybean or wheat than when maize is grown continuously. Such information on the role of legumes in rice and wheat systems is required.

Factors Affecting Residual Effects of Legumes

Work at ICRISAT indicated that the beneficial residual effect of legumes is influenced not only by the genotype but also the soil type. In pigeonpea, the genotypic differences in nodulation and N_2-fixation could be reflected in the magnitude of the beneficial effect of pigeonpea on a succeeding cereal crop grown on an Alfisol (Table 8). The beneficial effect of ICP 1-6, a medium-maturing and high-nodulating pigeonpea genotype on succeeding sorghum grain yield was equivalent to about 30 kg N ha^{-1} compared to fallow treatment. With ICPL 87, a low-nodulating but high-yielding pigeonpea genotype in multiple harvests, the beneficial effect was less and equivalent to only about 5 kg N ha^{-1} (Kumar Rao 1990). It is therefore important to select genotypes for both high yield and high nodulation characters in the short-duration pigeonpea. ICPL 87 grown in a multiple harvest system on a Vertisol had a residual effect of about 20 kg N ha^{-1} on a sorghum crop grown in the following rainy season, while ICP 1-6 had a residual effect equivalent to about 40 kg N ha^{-1} (Johansen et al. 1990). The mechanism of these beneficial effects of pigeonpea on following crops needs to be elucidated so as to exploit the same to achieve greater yields of following cereals without adversely affecting the sustainability of the system. The beneficial effects of pigeonpea could be due to leaf litter that is added to soil during crop season (Kumar Rao et al. 1983) or deep rooting that might facilitate recycling of nutrients from deeper horizons. The beneficial effect of pigeonpea could be also due to an increased available P pool as a result of P acquisition from insoluble Fe phosphates through root exudates (Ae et al. 1990).

Table 8: Nodulation, acetylene-reducing activity (ARA), and residual effect of pigeonpea genotypes (differing in nodulation), on the following cereal crop grown on an Alfisol at ICRISAT Center, Patancheru, India, rainy season 1987.[1]

	Nodule no. plant^{-1}		Nodule dry mass (mg plant^{-1})		ARA (µM C_2H_4 plant^{-1})		Residual effect on following cereal
Genotype	A	B	A	B	A	B	(equivalent to kg N ha^{-1})
ICPL 87	16	8	30	38	0.73	0.5	5
ICP 1-6	39	20	51	186	1.24	8.0	30
SE ±	3.8	± 3.7	±3.1	±31.5	±0.163	±1.88	
CV (%)	39	76	21	80	47	125	

[1] Means over irrigation levels; A = 35 days after sowing (DAS); and B = 58 DAS.

The growing season of the legume also affects the residual effect of the legume. For example, rainy season groundnut resulted in 45% more pearl millet *(Pennisetum glaucum)* grain compared to pearl millet following maize (Nambiar et al. 1982). However, if either groundnut or maize were grown in the post-rainy season no residual effect was observed on pearl millet grown in the following rainy season. Although other factors could be involved, it is possible that the observed effect of groundnut was due to leaf fall as a result of foliar diseases in the rainy season, whereas leaf fall due to foliar diseases was minimal during the post-rainy season.

In a field experiment at ICRISAT, Patancheru, a high N_2-fixing (HN) selection from the released chickpea cultivar G 130 (ICC 4948) nodulated 70% higher and had ARA activity 42% higher (mean of two different soil N levels) than its parent at 46 days after sowing. Its yield (a function of several parameters in addition to N acquisition) was only marginally higher (3.2-6.5%) than its parent and its low N_2-fixing selection (Rupela et al. 1995). But the beneficial effect of high N_2-fixing selection was visible in the following sorghum. The yield of sorghum (CSH 6) after the HN selection was higher (by 9.4%) than that grown after the parent line (Fig. 1). Performance of such selections of chickpea in rice-wheat cropping systems is being studied in a collaborative experiment between the Punjab Agricultural University, Ludhiana, India, and ICRISAT.

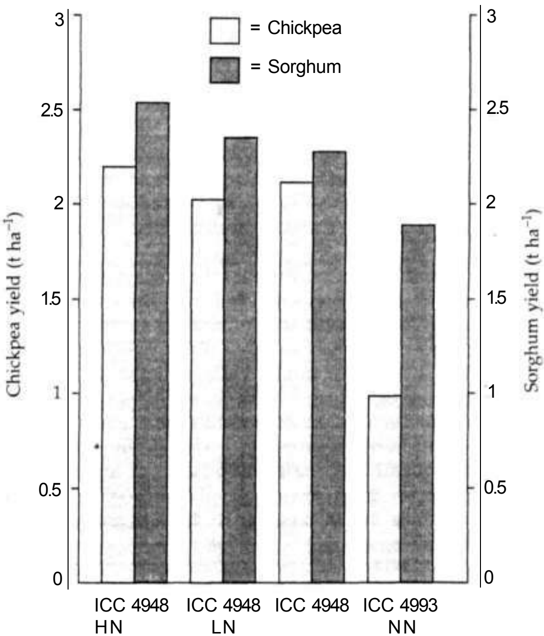

Figure 1: Yield of chickpea lines of different N_2-fixation capacities in post-rainy season 1992/93 and of sorghum grown after these in the rainy season 1993, ICRISAT, Patancheru, India (HN = high N_2-fixing chickpea line; LN = low N_2-fixing chickpea line; NN = nonnodulating chickpea line).
Source: Developed from Rupela et al. (1995).

FUTURE RESEARCH PRIORITIES

There is increasing evidence to suggest that productivity growth of rice-wheat systems in the IGP countries has slowed down. Production driving factors such as fertilizer-responsive high-yielding cultivars of cereals, increased use of fertilizers, and spread of irrigation have reached close to saturation point. Nutrient management was identified as a major issue to understand reasons for decline in rice-wheat yields by a workshop organized by the Rice-Wheat Consortium for IGP in October 1996 that reviewed many long-term soil fertility experiments set up in the region since early 1970s (Abrol et al. 1997). These experiments are focused on N, P, K, micronutrients, and organic fertilizers. Legumes are generally not included as treatments in such experiments (Abrol et al. 1997). We strongly feel that any such experiments should include legumes as one of the treatments.

Few experiments quantifying BNF have used dependable methods (e.g., ^{15}N-based). The experiments studying residual effect of legumes have largely used cereals as non-fixing controls. Non-nodulating lines of some legumes such as groundnut, pigeonpea, chickpea, pea (*Pisum sativum),* and soybean are now available and should separate BNF and non-BNF effects of legumes in relevant cropping systems. Such experiments on legumes and cropping systems of relevance to IGP need to be conducted. Researchers in some Asian countries have expressed inability to use ^{15}N methods because of inaccessibility of analytical facilities. Simple agronomic experiments involving nonnodulating legumes for quantifying BNF and their residual effects need to be examined. And where unavailable, appropriate nonnodulating lines from the legumes of interest need to be developed (Rupela and Johansen 1995a).

Legumes still remain part of rice-wheat cropping systems (Table 1) even though their area has significantly reduced over the years. On-farm BNF quantification (using ^{15}N or N-difference method) studies to identify/confirm factors that enhance contribution from BNF by legumes, in a cropping system perspective, should be conducted. The major thrust of these studies should be to devise strategies to maximize the net N input of a legume crop in the agro-ecosystem and the net N benefit to the following non-legume crop in rice- and wheat-based cropping systems. Simulation models are probably useful in quantifying the likely benefits of legumes in terms of saving of N fertilizer for the following cereal in rice-wheat systems in the IGP. Therefore, attempts should be made to develop and evaluate the relevant simulation models.

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Management of Legumes

6

Effective Management of Legumes for Maximizing Biological Nitrogen Fixation and Other Benefits

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ABSTRACT

The importance of legumes in sustainable crop production systems is well recognized. In the rice and wheat cropping systems of the Indo-Gangetic Plain, several legumes such as chickpea, lentil, pea, soybean, groundnut, mung bean, black gram, cowpea, and pigeonpea are grown depending upon rainfall pattern, water resources, geo-morphological features, domestic needs, and cropping systems. In the rice-wheat sequential cropping, short-duration legumes such as mung bean and cowpea offer great promise, but at present their adoption is negligible due to several management and social constraints.

The productivity of legumes in general is low due to low genetic yield potential and sub-optimal management practices. Several studies under the All India Coordinated Pulses Improvement Project (AICPIP) have clearly shown that with better management, the present level of productivity of most of the legumes could be almost doubled. Tillage, planting time, plant population, plant nutrition, irrigation, and weed management considerably influence biological nitrogen fixation and productivity of legumes and therefore their management needs to be optimized for the agroecological regions and production systems. A decrease in nodulation and nitrogenase activity in many legumes has been observed due to late planting, high plant population, drought, excess moisture, high dose of mineral nitrogen, and soil application of herbicides (oxyfluorfen, linuron, oxadiazon, and metribuzin). Enhanced nodulation and higher yield have been reported with timely planting, application of 20-40 kg sulfur ha^{-1} along with 17.5-26.5 kg phosphorus ha^{-1}, dual inoculation with *Rhizobium* and vesicular-arbuscular mycorrhizal fungi, irrigation at critical growth stages under moisture stress conditions, and efficient weed management. Deficiency of micronutrients such as zinc, molybdenum, and iron, which impair nodulation and grain yield, have been observed in some of the areas.

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The Indo-Gangetic Plain (IGP) is spread over Sind, Punjab, Baluchistan, and part of the North-West Frontier Province of Pakistan; part of Punjab, Haryana, Uttar Pradesh, Bihar (excluding Chhota Nagpur plateau), part of Madhya Pradesh, and West Bengal states of India; western part of Bangladesh, and the southern (Terai) part of Nepal. Rice (*Oryza sativa)* and wheat *(Triticum aestivum)* are the main cereal crops of this region grown either in sequential cropping or rotated with other crops depending upon rainfall, irrigation facilities, geo-morphological features, and domestic needs.

Rice-wheat crop rotations occupy the largest area under input-intensive agriculture for providing food security to this region. However, cultivation of rice and wheat in sequential cropping over years has led to several problems such as "soil sickness", deficiency of some of the plant nutrients [sulfur (S) and zinc (Zn)], lowering of the water table, and soil salinization. This has sensitized agricultural scientists, policy makers, and the farming community to seek sustainable cropping systems having legumes as one of the components.

The important food legumes grown in the IGP are chickpea *(Cicer arietinum),* pigeonpea *(Cajanus cajan),* black gram *(Vigna mungo),* mung bean *(Vigna radiata),* soybean *(Glycine max),* groundnut *(Arachis hypogaea),* lentil *(Lens culinaris),* pea *(Pisum sativum),* and cowpea *(Vigna unguiculata).* Rice-chickpea, rice-lentil, rice-pea, pigeonpea-wheat, soybean-wheat, groundnut-wheat, black gram-wheat, and rice-mustard *(Brassica* sp.)/potato *(Solanum tuberosum)-b\ack* gram/mung bean are the popular crop rotations involving legumes. In rice-wheat sequential cropping, efforts have been made to introduce short-duration mung bean or fodder cowpea as a catch crop during summer (Apr-Jun). With good management, 800-1000 kg seed yield ha^{-1} of mung bean has been obtained in the northeast plains of India. However, the availability of irrigation water and mung bean genotypes of 50-60 days duration are the major constraints to large-scale adoption of this system.

An effort has been made to review the current status of knowledge on influence of agronomic management practices on nodulation, biological nitrogen fixation (BNF), and productivity of various grain legumes in the IGP and focus on future research priorities.

LEGUMES IN CROPPING SYSTEMS

Legumes are considered to be an important component of subsistence cropping systems of the semi-arid tropics because of their ability to convert atmospheric nitrogen (N) into the assimilable form of ammonia, to add substantial amounts of organic matter to the soil, and to grow better than many other crops with low inputs under harsh climatic and edaphic conditions. The global concern about sustainable agricultural systems further highlights the significance of legumes, which offer a renewable source of energy through BNF. Annual global BNF has been estimated at around 175 million t of N of which about 79% is accounted by terrestrial fixation (Burns and Hardy 1975). This clearly shows that legumes offer an economically attractive and ecologically sound means of reducing external fertilizer N input and improving the quality and quantity of internal resources. Depending upon physical, environmental, and biological factors, legumes can fix N_2 up to 450 kg ha^{-1} (e.g., soybean). A considerable part of N_2 fixed by legumes is, however, harvested and removed as grains (Table 1). The N left in the legume residue generally benefits succeeding crops. Myers and Wood (1987) proposed a simple conceptual model for the utilization of N by a following crop as:

$$Nc = NI \times P \times (1 - NHI)\ Fm \times E$$

where Nc is the amount of N derived from the previous crop taken up by the following crop, Nl is the amount of N in the previous legume crop, P is the proportion of the legume N derived from fixation, NHI is the nitrogen harvest index ideally defined as the ratio of N in seed to N in total plant biomass usually at maturity, Fm is the proportion of residual N that is mineralized, and E is the efficiency of utilization of this mineral N. This suggests that the N contribution of legumes to the succeeding crops depends on both amount of N fixed as well as its partitioning. To maximize the contribution of N to subsequent crops it is necessary to maximize N_2-fixation, minimize NHI, maximize N mineralization from the legume residue, and maximize E. The distribution of fixed N_2 by soybean, mung bean, and *Sesbania* was measured by Myers and Wood (1987) using the isotope dilution method. In this study (Table 1), 70% of N in soybean, 52% in mung bean, and 30% in black gram was translocated to seeds. The remaining 83-141 kg N ha^{-1} was left in the crop residue, of which 54-98 kg N ha^{-1} was attributable to fixation.

Table 1: Estimates of nitrogen (N) fixation and removal by some legume crops.

Crop	N fixed (kg ha^{-1})	NHI[1]
Groundnut	240-260	0.49
Chickpea	120-140	0.80
Soybean	93-138	0.80-0.89
Cowpea	47-188	0.53-0.69
Mung bean	112	0.69-0.81
Sesbania	126-141	NR[2]
Black gram	55-72	0.41-0.65
Lablab bean	66-208	0.48-0.56
Pigeonpea	150	0.52-0.62

[1] NHI = nitrogen harvest index.

[2] NR = not recorded.

Source: Myers and Wood (1987).

The mineralization of this N depends on the C/N ratio of the residue (Nnadi and Balasubramanian 1978), soil moisture, soil temperature, and the duration of mineralization. It has been estimated in experiments that a good crop of summer mung bean benefits the subsequent rice crop to an extent of 20-30 kg N ha^{-1} (Chandra 1988). Maskina et al. (1987) reported that the inclusion of summer green manure increased yield of rice by 141% over fallow, and 15% over mung bean grown for grain purposes. Sharma et al. (1985) reported an increase in soil nitrate from 73 kg N ha^{-1} in Apr to 223 kg N ha^{-1} in Jun during the growth of a mung bean crop between wheat and rice crops on a sandy loam soil in Punjab, India. However, it is not clear if the increase in soil nitrate reported in the study came from the fixation by the mung bean crop or was due to the effect of soil heating during summer (Chauhan et al. 1988).

The beneficial effect of legumes in cropping systems is not solely due to BNF but due to several other associated mechanisms such as increased nutrient availability, improved soil structure, reduced disease incidence, and increased mycorrhizal colonization (Wani and Lee 1995). Bullock (1992) concluded that rotation with legumes does not provide as much N as fertilizer replacement methodology estimates and that much of the yield benefit which has been credited to N contributions is actually due to other factors. Introduction of legumes in crop rotation can influence soil-borne pathogens such as nematodes, in addition to improving soil structure (Karlen et al. 1994). Hulugalle and Lal (1986) found that bulk density was always lower in plots with pigeonpea and maize *(Zea mays)* rotation than in well-fertilized continuous maize. One of the reasons for lowering of bulk density could be that many legumes return considerable organic matter through fallen leaves, which can be as high as 15% of the total above-ground recoverable dry matter. Increased soil organic matter also enhances the water infiltration rates and water-holding capacity (Hudson 1994).

PRODUCTIVITY OF LEGUMES

The genetic yield potential of legumes compared with cereals is, generally, low. Tne primitive characters associated with legumes, e.g., indeterminate growth, perennial habit, prolonged flowering period, deep root system, compound leaves, considerable flower drop, and shattering of mature pods are testimony of the fact that their domestication was aimed at survival under adverse" conditions rather than high yield. Such criteria of domestication led to several weak links in productivity of legumes which is far below the potential level of productivity obtained at research stations and well-managed demonstration plots. The average productivity of important legumes grown in the IGP of India is below 1.2 t ha^{-1} (Table 2). The productivity of winter legumes is comparatively higher than the rainy season legumes due to more favorable weather conditions.

Results of frontline demonstrations under the All India Coordinated Pulses Improvement Project (AICPIP) during 1992/93 showed that with the component technology, the productivity of pulse crops could be considerably increased. The mean yield of 37 demonstrations of pigeonpea with fertilizer management was 1.41 t ha^{-1} as against 1.10 t ha^{-1} with no fertilizer (Table 3). Similarly, improved weed management recorded 1.52 t ha^{-1} grain yield as against 1.28 t ha^{-1} with traditional practice. Insect management technology alone resulted in a 56% increase in seed yield (Lal et al. 1994). Similar trends have also been observed in chickpea, mung bean, and black gram (Table 3).

Table 2: Area, production, and productivity of important legumes in the Indo-Gangetic Plain of India, 1995/96.

State	Description[1]	Chickpea	Pigeonpea	Black gram	Mung bean
Uttar Pradesh	A	112.0	510.0	278.4	138.5
	P	780.0	490.0	123.7	65.8
	Y	0.7	1.0	0.4	0.5
Bihar	A	120.0	70.0	70.2	181.8
	P	90.0	60.0	36.4	101.0
	Y	0.7	0.9	0.5	0.6
Haryana	A	380.0	20.0	1.3	11.4
	P	390.0	20.0	0.6	5.1
	Y	1.0	0.8	0.5	0.4
Punjab	A	20.0	9.8	6.2	52.5
	P	20.0	8.6	2.1	43.8
	Y	0.9	0.9	0.3	0.8
West Bengal	A	20.0	3.8	77.3	5.3
	P	20.0	2.4	31.6	3.2
	Y	0.8	0.8	0.4	0.6
Madhya Pradesh	A	2660.0	400.0	513.3	131.0
	P	1990.0	300.0	175.2	42.6
	Y	0.8	0.8	0.3	0.3

[1]A = area ('000 ha); P = production ('000 t); Y = yield (t ha^{-1}).

Source: GOI (1997).

Table 3: Effect of management technology on the productivity of legumes during 1992/93.[1]

			Grain yield (t ha^{-1})		
Technology	Legume crop	Number of demon-strations	Improved techno-logy	Local techno-logy	Increase in yield (%)
Fertilizer management	Pigeonpea	37	1.41	1.10	38
	Mung bean	1	0.60	0.50	20
	Lentil	4	1.43	1.11	29
Weed management	Pigeonpea	20	1.52	1.28	26
	Chickpea	3	1.76	1.57	12
	Mung bean	1	1.09	0.93	18
	Black gram	13	0.88	0.75	18
Insect management	Pigeonpea	29	1.11	0.71	56
	Chickpea	25	1.25	0.98	28
	Mung bean	9	0.76	0.53	45
	Black gram	2	1.21	0.86	42

[1]All India Coordinated Pulses Improvement Project trial.

Bahl and Baldeo (1981) analyzed chickpea data of coordinated trials and minikits in some states of northern India and found a gap of 71% between research station yield and state average yield. A range of climatic, edaphic, and biotic factors constrained the productivity of chickpea. The relative importance of each factor, however, varies from region to region due to diversity of agroecological conditions.

MANAGEMENT OF LEGUMES

As indicated above, management factors play a key role in enhancing BNF and productivity of legumes. Tillage practices, planting time, plant population, plant nutrition, irrigation practice, and weed management considerably influence BNF and crop productivity. The effect of each of these factors is discussed briefly.

Tillage

In the IGP, legumes are cultivated on a wide range of soils varying in texture, from loamy sand in Punjab to heavy clay in West Bengal. In the light-textured soils, tillage techniques to ensure optimum moisture availability in the seeding zone need greater attention whereas in the heavy-textured soils good seed bed preparation, especially after rice, is of immense significance.

During winter, legumes such as chickpea and lentil are grown on residual moisture and deep planting is often done to ensure placement of seeds in the moist zone. This reduces nodulation and N_2-fixation due to low concentration of soil oxygen. Similarly, in heavy-textured soils, poor aeration and soil compactness often lead to poor nodulation. Work on tillage management of rice-based sequential cropping systems at the Indian Institute of Pulses Research (IIPR), Kanpur showed that relay planting of legumes [chickpea, lentil, pea, khesari *(Lathyrus sativus),* and faba bean *(Vicia faba)]* and oilseed [linseed *(Linum usitatissimum)]* in the standing crop of rice under zero tillage gave low yields as compared with that grown after harvest of rice followed by cross harrowing (Table 4) (Kumar and Ali 1995). Among various *rabi* crops, khesari recorded highest yield (2.33 t ha^{-1}) followed by faba bean (1.41 t ha^{-1}). Tomar and Singh (1991) also reported higher uptake of N and phosphorus (P) by lentil with one plowing as compared with zero tillage on sandy loam soils at Agra, Uttar Pradesh.

In rainy season legumes, especially pigeonpea, groundnut, and soybean, plant population is often vitiated due to water stagnation or poor drainage. Raised and ridge-furrow beds have been found quite effective in ensuring optimum plant stand and increased crop productivity. In multilocational studies on short-duration pigeonpea in the northwest plain zone of India, raised beds of 2.7-m width gave mean yield of 1.63 t ha^{-1} as against 1.25 t ha^{-1} in flat beds (Table 5). Planting on ridges in a ridge-furrow bed system was also beneficial (Ali 1995).

Table 4: Yield of legumes and oilseeds as influenced by cropping sequence anc tillage treatments.

Treatment	Rice yield (t ha^{-1}) Grain	Straw	*Rabi* crop grain yield (t ha^{-1})
Rice-lentil	4.43	9.29	1.11
Rice-pea	4.41	9.29	1.15
Rice-linseed	4.47	9.14	1.20
Rice-faba bean	4.49	9.42	1.41
Rice-khesari	4.43	9.25	2.33
Rice-chickpea	4.47	2.22	1.12
SE	±1.13	±0.18	±0.04
LSD (P = 0.05)	NS[1]	NS	0.13
Tillage practice			
No tillage	4.43	9.27	1.32
Tillage (2 harrowings)	4.47	9.26	1.46
SE	±0.05	±0.10	±0.03
LSD (P = 0.05)	NS	NS	0.07

[1]NS = not significant.

Source: Kumar and Ali (1995).

Table 5: Grain yield of pigeonpea as influenced by bed configuration at three locations in northwest plain zone of India, 1994-95.

Planting method	Grain yield (t ha^{-1}) Hisar	Ludhiana	Pantnagar	Mean
Flat bed	0.71	1.69	1.34	1.25
Planting on ridges	0.96	1.40	1.95	1.44
Raised bed at 2.7 m width	1.18	NT[1]	2.08	1.63
Flat sowing and making furrows 30 DAS[2] at 2.7 m width	1.02	2.05	1.53	1.53
SE	±0.03	±0.04	±0.05	

[1]NT = not tested. [2]DAS = days after sowing.

Source: Ali (1995).

Planting Time

Planting time is a non-monetary input which can have a profound effect on productivity and success of the high intensity crop production systems. It causes a considerable change in the plant environment in respect to temperature, photoperiod, and availability of soil moisture. The optimum time of sowing of chickpea in northern Indian states is from mid-Oct to mid-Nov. Studies on planting dates of chickpea at Ludhiana during 1991/92 to 1992/93 showed that delayed planting beyond 5 Nov significantly reduced number of nodules, nodule dry weight, and leghaemoglobin content in chickpea (Sharma et al. 1995). The optimum planting time for maximizing nodulation was between 20 Oct and 5 Nov .The leghaemoglobin content in the 20 Oct planting was 2.29-2.73 mg g^{-1} of nodule as against 1.28-1.37 mg g^{-1} of nodule in the 20 Nov planting (Table 6). Govind Reddy et al. (1991) reported that 15 Oct was the optimum time of planting for *rabi* (post-rainy season) pigeonpea at Kharagpur (West Bengal). When compared to the 15 Oct planting yield losses of 31.8% occured in 30 Oct planting and 66.6% in 14 Nov planting. During the rainy season, advance planting of pigeonpea (5 May) registered an increase of 17.6% in grain yield over a 20 May planting on loamy sand soil of Ludhiana (Rana and Malhotra 1993). The yield attributes, nodule number, and dry weight as well as seed yield of soybean were increased significantly when the crop was sown on 18 Jul in comparison with 29 Jun and 7 Aug sowings under West Bengal conditions (Majumdar and Behra 1991).

Table 6: Effect of dates of planting on nodulation and leghaemoglobin content of chickpea at Ludhiana, India.

Planting date	Nodules (number $plant^{-1}$)	Dry weight of nodules (mg $plant^{-1}$)	Leghaemoglobin content (mg g^{-1} nodule)
1991/92			
20 Oct	18.4	67.1	2.29
5 Nov	20.3	66.3	1.66
20 Nov	11.8	45.8	1.28
SE	±0.52	±4.16	±0.07
1992/93			
20 Oct	24.4	74.1	2.73
5 Nov	23.1	73.5	1.73
20 Nov	15.2	51.1	1.37
SE	±136	±028	±057

Source: Sharma et al. (1995).

Plant Population

Low plant stand is one of the major constraints for low productivity of pulses especially under rainfed conditions. Several studies under AICPIP have shown that the grain yield of pigeonpea and lentil increased with the corresponding increases in plant density up to certain limits. In the case of short-duration pigeonpea, 15-16 plants m^{-2} were adequate. In the case of chickpea, 22-30 plant m^{-2} for timely planting (mid Oct) and 30-40 plants m^{-2} for late (mid-Dec) planting were found optimal under northern Indian conditions. Under late-sown conditions, the plant growth is often restricted and therefore a higher population is desired for compensating the yield loss $plant^{-1}$.

Adverse effects of high seed rates on nodulation have been reported. Venkateshwarlu and Ahlawat (1993) found that a seed rate of 60 kg ha^{-1} significantly depressed nodulation in lentil at Delhi, India as compared to a seed rate of 40 kg ha^{-1}. However, grain yield was more at the high seed rate.

Vaishya et al. (1995) studied the effect of seed rates on nodulation and yield of chickpea at Faizabad, Uttar Pradesh. They found that on silty clay loam soils increasing seed rate from 75 kg ha^{-1} significantly decreased number of nodules $plant^{-1}$ counted at 90 days after sowing (DAS). The grain yield also decreased progressively with increasing seed rate (Table 7).

Table 7: Effect of seed rates on nodulation and grain yield of chickpea grown at Faizabad, Uttar Pradesh, India on a silty clay loam during 1987/88.

Seed rate (kg ha^{-1})	Nodules[1] (number $plant^{-1}$)	Grain yield (t ha^{-1})
75	29.5	1.81
100	19.7	1.73
125	17.2	1.67
LSD (P = 0.05)	1.6	NS[2]

[1] Counted at 90 days after sowing.
[2] NS = not significant.
Source: Vaishya et al. (1995).

Nutrient Management

Adequate and balanced supply of plant nutrients is essential for achieving and sustaining high productivity. Nutrient management in legumes in multiple cropping systems is rather complex and has received low priority in the past. Most of the studies on fertilizer use in legumes are individual crop based and thus the results have only limited application in various cropping systems involving cereals and pulses.

Macronutrients

Nitrogen is the most critical plant nutrient for growth and yield of cultivated crops. However, legumes derive a large proportion of their N requirement through BNF and consequently only a starter dose of 20-25 kg N ha^{-1} is usually recommended. In fertilizer experiments on farmers' fields under the All India Coordinated Agronomy Research Project (AICARP), chickpea showed substantial response to 20 kg N ha^{-1}. The N-use efficiency was 8.5-19.5 kg grain kg^{-1} N (Prasad and Subbiah 1982). When the N_2-fixing system is operative, chickpea does not respond to N beyond 20 kg ha^{-1} (Saxena and Sheldrake 1980). However, in rice fields where the rhizobial population is often low, late-sown chickpea responds well up to 40 kg N ha^{-1} (Ali 1994a). Pea, generally grown under irrigated conditions, has also shown good response to high doses of N. Multilocational studies under AICPIP during 1991-94 showed that dwarf pea cultivar Apama responded favorably to 40-60 kg N ha^{-1} (Ali et al. 1994). These results clearly show that response to N is considerably influenced by native *Rhizobium* population and moisture status of soil. Common bean *(Phaseolus vulgaris),* which has been introduced as a winter crop in the frost-free belt of northern India, does not nodulate with native *Rhizobium* strains and consequently responds well up to 120 kg N ha^{-1} (Ali and Lal 1989).The application of N may not only be directly beneficial to the legume but may also benefit the succeeding crops. For example, in a rice-wheat rotation experiment, application of 80 kg N ha^{-1} as urea to the rice crop had no effect on wheat yield, but application of 40 kg N ha^{-1} as urea to *Sesbania aculeata* grown as green manure to rice combined with 40 kg N ha^{-1} as urea to rice increased wheat yield by 0.7 ha^{-1} (Mahapatra amd Sharma 1989). This was attributed to improvement in soil physical conditions after puddling of the field for rice production.

Phosphorus is the second most critical plant nutrient overall, but for legumes it assumes primary importance. The soils of the IGP are generally low to medium in available P content and therefore application of 17-26 kg P ha^{-1} has shown favorable effects in grain legumes (Ahlawat and Ali 1993). Compared with other pulses, chickpea is more efficient in taking up P from soil as it secretes acid exudates from roots which helps in solublizing Ca-P (Ae et al. 1991). In pigeonpea, response to applied P varies considerably from 17 kg ha^{-1} to 43 kg ha^{-1} P depending upon P status of soil (Chauhan and Singh 1981). Kasturi (1995) reported that application of 26.4 kg P ha^{-1} significantly improved seed yield, nodulation, and nitrogenase activity in pea (Table 8).

Table 8: Effect of moisture stress and nutrients on root nodulation, nitrogenase activity at 90 days after sowing and yield of pea grown on loamy soil at New Delhi, India.[1]

Treatment	Nodules (number $plant^{-1}$)	Dry weight of nodules (mg $plant^{-1}$)	Nitrogenase activity (µmoles C_2H_4 $plant^{-1}$ h^{-1})	Grain yield (t ha^{-1})
Moisture stress				
At vegetative stage	27.9	51.7	3.96	1.82
At flowering stage	33.7	59.6	4.59	1.55
At pod filling stage	33.6	64.3	4.95	1.73
No stress (control)	33.9	66.8	5.14	2.11
Nutrient level[2] (kg ha^{-1})				
0 P (Control)	27.6	49.3	3.76	1.47
13.2 P	32.4	62.1	4.78	1.87
26.4 P	35.5	72.9	5.43	2.07
0 S (control)	29.4	54.9	4.22	1.65
40 S	32.1	61.2	4.72	1.83
40 S + 5 Zn	33.8	65.7	5.05	1.93

[1]Data are mean of 1992/93 and 1993/94.

[2]P = phosphorus; S = sulfur; Zn = zinc.

Source: Kasturi (1995).

Sharar et al. (1976) found that yield of lentil in Pakistan increased with increasing levels of P. However, no improvement in yield with P application on soils rich in P was observed. Late-sown lentil responded up to 28 kg P ha^{-1} on sandy loam soils of Delhi (Watt 1988).

Experiments on farmers' fields were conducted under AICARP to determine the response of pulse crops to applied P. Based upon results of 709 trials on chickpea, 583 on pea, 173 on mung bean, and 177 on black gram, it was found that the mean response to each kg of P applied at 29.4 kg P ha^{-1} was 3.1, 6.0, 1.6, and 3.0 kg grain respectively (Prasad 1979).

In summer mung bean, application of 26 kg P ha"[1] significantly increased nodulation and yield in West Bengal (Sarkar and Banik 1991). Nitrogen application beyond 20 kg ha^{-1} depressed nodulation but the yield increased significantly. The P needs of one legume intercropped with another is usually higher than that of the sole crop. In pigeonpea/groundnut intercropping, when both crops received 17 kg P ha^{-1}, productivity was higher than that of sole crops (Pareek and Turkhede 1991). Since the soils of the IGP are generally rich in potassium (K), response to applied K is either low or absent.

In recent years, S deficiency has been observed in the rice-wheat belt of northern India due to increased cropping intensity and use of S-free fertilizers, e.g., urea and diammonium phosphate. The S deficiency is more pronounced on productivity of legumes than cereals due to comparatively higher S need of the former for producing grain. In multilocational studies under AICPIP during 1991-94, pigeonpea responded favorably to 40 kg S ha^{-1} whereas chickpea, lentil, black gram, and mung bean showed significant response only up to 20 kg S ha^{-1} (Table 9). The mean extra productivity at these levels of S was 392 kg ha^{-1} in pigeonpea, 476 kg ha^{-1} in chickpea, 450 kg ha^{-1} in lentil, 166 kg ha^{-1} in black gram, and 194 kg ha^{-1} in mung bean (Ali and Singh 1995).

Table 9: Productivity (t ha^{-1}) of different grain legumes as influenced by sulfur use in the Indo-Gangetic Plain of India during 1991-94.

		Sulfur rate (kg ha^{-1})		
Legume	No. of locations	0	20	40
Chickpea	5	1.42	1.86	1.90
Lentil	3	1.02	1.47	1.46
Pigeonpea	6	1.19	1.35	1.52
Black gram	3	0.83	1.00	0.95
Mung bean	3	0.99	1.18	1.16

Source: Ali and Singh (1995).

High nodulation, nitrogenase activity, and seed yield in pea with soil application of 40 kg S ha^{-1} has also been reported by Kasturi (1995). Combined use of 5 kg Zn ha^{-1} and 40 kg S ha^{-1} further improved BNF and grain yield (Table 8). Kandpal and Chandel (1993) studied effect of levels and sources of S on nodulation and N_2-fixation in soybean on silty clay loam soils of Pantnagar in Uttar Pradesh. They found that irrespective of sources of S, nitrogenase activity and N_2-fixation increased with increasing level of S up to 40 kg ha^{-1} (Table 10). The amount of N_2 fixed at 40 kg S ha^{-1} as gypsum was 170.1 kg ha^{-1} and as pyrite 175.2 kg ha^{-1}, as against 49.2 kg ha^{-1} without S. Similarly, the nitrogenase activity at 40 kg S ha^{-1} was 43.6

μmoles C_2H_4 plant^{-1} h^{-1} with gypsum and 44.9 μmoles C_2H_4 plant^{-1} h^{-1} with pyrite as compared with 12.7 μmoles C_2H_4 plant^{-1} h^{-1} without S. Ali and Singh (1995) reviewed results of coordinated trials of AICPIP and concluded that different sources of S, i.e., gypsum, pyrite, and single superphosphate (SSP) were almost identical in their efficacy.

Table 10: Effect of sulfur on nitrogenase activity and nitrogen fixation in soybean cv. PK 327 at 60 days after sowing on silty clay loam soil at Pantnagar, Uttar Pradesh, India.

Source and level of sulfur	Nitrogenase activity (μmoles C_2H_4 plant^{-1} h^{-1})	Nitrogen fixed (kg ha^{-1})
Gypsum		
10 kg S ha^{-1}	14.9	58.3
20 kg S ha^{-1}	23.7	98.2
30 kg S ha^{-1}	31.0	120.9
40 kg S ha^{-1}	43.6	170.1
Pyrite		
10 kg S ha^{-1}	15.0	58.4
20 kg S ha^{-1}	24.0	93.7
30 kg S ha^{-1}	30.6	119.5
40 kg S ha^{-1}	44.9	175.2
Control (inoculated)	12.7	49.2
LSD (P = 0.05)	1.7	6.2

Source: Kandpal and Chandel (1993).

Micronutrients

Response of legumes to micronutrients, including Zn, molybdenum (Mo), iron (Fe), and manganese (Mn) have also been observed. In chickpea, application of 25 kg $ZnSO_4$ ha^{-1} improved nodulation, root growth, and yield (Singh and Gupta 1986) and also increased uptake of Zn, Fe, and P (Dravid and Goswami 1987). Lentils are highly susceptible to Zn deficiency and an improvement in yield with soil application of 12.5-15.0 kg $ZnSO_4$ ha^{-1} has been observed. Foliar spray of 0.5 kg $ZnSO_4$ ha^{-1} with 0.25 kg lime has also been found effective in correcting Zn deficiency in chickpea and lentil (Saxena and Singh 1977).

Molybdenum, being a constituent of nitrate reductase and nitrogenase enzymes, considerably influences BNF. Srivastava (1993) observed that application of Mo increased number of nodules, dry weight of nodules, nitrogenase activity, and grain yield of pea. With application of 0.5 kg Mo ha^{-1}, the number of nodules was 22.8 plant^{-1}, dry weight of nodules was 24.2 mg plant^{-1}, nitrogenase activity was 4.2 μmoles C_2H_4 plant^{-1} h^{-1}, and grain yield of pea was 1.6 t ha^{-1} whereas in the control the respective values were 21.7 plant^{-1}, 22.9 mg plant^{-1}, 3.7 μmoles C_2H_4 plant^{-1} h^{-1}, and 1.5 t ha^{-1}. In calcareous soils of northern Bihar, application of 5-10 kg borax ha^{-1} has proved quite effective in improving yield of chickpea (Ali 1995). Multilocational trials on micronutrients showed that foliar application of 0.5 kg $FeSO_4$ ha^{-1} improved productivity of chickpea by 450 kg ha^{-1} over the control (Takkar and Nayyar 1986). Since genotypic variation in susceptibility to deficiency of micronutrients has been observed in chickpea, lentil, and pigeonpea, efforts should be made to choose cultivars which do comparatively better in soils deficient in micronutrients (Ahlawat and Ali 1993).

Biofertilizers

The value of biofertilizers in sustainable crop production is well recognized. Legumes possess the intrinsic capacity of fixing atmospheric N in their root nodules through *Rhizobium* which needs to be fully exploited.

The quantum of N_2 fixed by legumes is influenced by several physical, environmental, and biological factors (Kumar Rao and Rupela 1998). The level of native rhizobial population appears to be one of the major constraints for poor nodulation. Under AICPIP, soil samples from 506 locations were collected to estimate the population of *Rhizobium.* It was observed that 79% of the samples had low to medium bacterial population. Favorable effects of inoculation on nodulation and yield have been reported by several workers. In a multilocational study under AICPIP, seed inoculation enhanced the productivity of different pulses by 10-15% (Chandra and Ali 1986). Tilak and Dwivedi (1991) reported a significant increase in colonization of vesicular-arbuscular mycorrhiza (VAM), nodules plant^{-1}, dry weight of nodules, and nitrogenase activity of chickpea with *Glomus versiforme* inoculation.

Legume species not only differ in nodulation but cultivars within species also differ significantly, suggesting that host factors are important determinants of nodulation. Besides the specificity for root infection, the development of root nodules is influenced by both bacterial and plant genes. Patel et al. (1986) found significant interaction between *Rhizobium* strains and genotypes of chickpea. In chickpea cv BG 209, strain KG 31 was most effective whereas strain F 75 in cvs Dohad yellow and JG 315, and strain F 6 in cv Chafa were more effecive (Table 11). Studies on effectiveness of single and multi-strains of *Rhizobium* on chickpea cv BDN 9-3 did not show any advantage of multi-strain inoculation over single strain (Pedgaonkar and Raut 1985). Bhattacharya and Sengupta (1984) evaluated 21 genotypes of lentil and observed that genotypes with high coralloid nodules had better nodulation. Further, they found that genotypes with pink nodules gave higher yield than other genotypes.

The symbiotic association between plant roots and mycorrhizal fungi has received greater attention in recent years. The VAM enhances plant growth by improved mineral nutrition particularly P and water uptake on account of the hyphal network originating from mycorrhizal roots which make close contact with the soil mass. Rao et al. (1986) observed higher N and P concentration in shoots of chickpea due to *Glomus fasciculatum* inoculation which was almost equivalent to the effect of seed inoculation with *Rhizobium.* Reddy (1992) reported that both *Rhizobium* and VAM inoculation improved number of nodules, dry weight of nodules, and seed yield in lentil and were

Table 11: Effect of *Rhizobium* inoculation on the grain yield of four genotypes of chickpea at Dohad (Gujarat) during 1978/79 to 1980/81.

	Grain yield (t ha^{-1})				Increase in yield
Rhizobium strain	BG 209	Dohad yellow	JG 315	Chafa	over control (%)
F 6	3.02	3.10	3.49	2.93	49
Ca 181	2.78	3.02	3.49	2.62	42
KG 31	3.17	2.54	4.24	1.89	41
F 75	3.10	3.17	4.44	2.54	58
H 45	2.54	2.94	3.41	2.41	41
Uninoculated control	1.91	1.91	2.62	1.98	
	Genotypes (G)	*Rhizobium* strains (S)		G x S	
SE	± 0.34	± 0.14		± 0.29	
LSD (P = 0.05)	NS[1]	0.41		NS	

[1]NS = not significant.

Source: Patel et al. (1986).

at par with each other (Table 12). Dual inoculation with *Rhizobium* and VAM further increased nodulation and yield.

Table 12: Effect of biofertilizers on root nodulation at 80 days after sowing and grain yield of lentil during 1989/90.

Biofertilizer[1]	Nodules (number $plant^{-1}$)	Dry weight of nodules (mg $plant^{-1}$)	Grain yield (t ha^{-1})
Uninoculated control	17.4	4.2	0.84
Rhizobium	26.1	5.4	1.03
VAM	20.5	6.3	1.09
Rhizobium + VAM	29.8	7.2	1.19
LSD (P = 0.05)	NA[2]	NA	0.04

[1]VAM = Vesicular arbuscular mycorrhiza.

[2]NA = LSD values not available.

Source: Reddy (1992).

Irrigation Management

Drought and excess moisture are deterimental to BNF and growth of legumes (Smith 1987; Kirda et al. 1989). The ability of these crops to survive under low soil moisture conditions/drought is, however, only at the cost of biological and economic yields. There is evidence that cytokinins induce tolerance in plants to moisture stress (Sharma et al. 1995). *Rhizobium* strains are capable of producing cytokinins. Therefore, it is likely that nodules impart some tolerance to legumes against drought. Once nodules disintegrate, this mechanism may cease to operate and plants would become more susceptible to moisture stress.

Drought of different intensities is experienced in rainfed areas of the IGP at seedling, vegetative, and terminal growth stages of legumes and causes irrepairable damage to crops and also vitiates plant stand. *Rhizobium* bacteria are less severely affected by drought than host plants. Sprent et al. (1988) viewed that while the soil may be sufficiently dry to prevent plant growth, it may still contain enough wet microsites to allow the survival and even growth of rhizobial inoculum. The ability of rhizobia to survive under dry conditions varies with species, soil type, and other factors. When enough moisture becomes available to permit plant growth, pockets of rhizobia multiply, and spread in soil pores which have become wet. Efforts to develop short-duration cultivars, having drought tolerance characteristics is a long-term strategy. The immediate solution lies in diverting some irrigation water to legumes which do comparatively better at low levels of irrigation than cereals.

Response to limited irrigation has been observed in most of the grain legumes in India (Ali 1994b). Among various crops, common bean *(Phaseolus vulgaris)* was found to be more responsive to irrigation, followed by pea. The success of mung bean as a catch crop in the rice-wheat system is solely dependent upon adequate supply of irrigation. Late-sown chickpea in sequence with rice also needs more irrigation than the normal planted crop probably due to restricted root growth.

Various approaches, e.g., crop growth stage, frequency, and cumulative pan evaporation, have been adopted for scheduling irrigation. Pod initiation has been found to be the most critical stage in most of the legumes. However, the initial profile moisture and soil type largely determine the requirement of subsequent irrigation. Pal and Jana (1991) found that in summer mung bean, irrigation at vegetative stage was most critical. Nodulation was also severely affected by delayed irrigation (Table 13). In pea, moisture stress at an early stage (vegetative) considerably reduced nodulation, nitrogenase activity, and seed yield (Kasturi 1995). The nitrogenase activity of plants subjected to moisture stress at the vegetative stage was 3.96 μmoles C_2H_4 plant^{-1} h^{-1} as compared with 4.95 µmoles C_2H_4 plant^{-1} h^{-1} when stress was imposed at pod development (Table 8).

Table 13: Effect of irrigation on nodulation and yield of mung bean[1].

Irrigation level	Nodules (number plant^{-1})	Fresh weight of nodules (mg plant^{-1})	Grain yield (t ha^{-1}) 1982	Grain yield (t ha^{-1}) 1984
Rainfed (Control)	10.3	26	1.20	1.56
One at vegetative (V)	27.0	55	1.48	1.80
One at pod development (P)	41.0	27	1.72	1.90
Two, at V P	27.2	58	1.92	2.02

[1]Statistical analysis values are not available in the original publication.

Source: Pal and Jana (1991).

Using a climatological basis for calculating irrigation requirement, irrigation at an irrigation water/cumulative pan evaporation (IW/CPE) ratio of 0.25 in medium-duration pigeonpea (180-200 days) on clayey soils of

Navsari, Gujarat (Patel and Patel 1995), 0.4 in chickpea on sandy loam soils of Delhi (Prabhakar and Saraf 1991), and 0.7 in soybean on clay loam soils of Raipur, Madhya Pradesh (Pandey et al. 1995) in India have been found to be most efficient. A higher number of nodules and their dry weight were recorded both at 45 and 55 DAS in soybean with irrigation scheduled at IW/CPE ratio of a 0.07 as compared with 0.5 (Table 14). At 70 DAS, the nodule formation was reduced at all the levels of irrigation. Pal and Lal (1993) at Pantnagar, Uttar Pradesh observed higher nodulation in summer planted mung bean when irrigation was scheduled at 10 cm cumulative pan evaporation (CPE) as compared with that at 15 and 20 cm CPE thereby indicating a positive interaction between soil moisture and root nodules.

Table 14: Effect of irrigation on nodulation and grain yield of soybean at Raipur, Madhya Pradesh, India during 1990/91.

	Nodules at DAS[1] (number plant^{-1})			Dry weight of nodules at DAS (mg plant^{-1})			Grain yield
Irrigation treatment[2]	45	55	70	45	55	70	(t ha^{-1})
I_1	18	25	19	95	173	143	1.52
I_2	13	16	14	75	130	113	1.21
I_3	17	18	14	91	139	130	1.27
I_4	18	24	14	93	169	129	1.17
I_5	15	21	16	77	144	131	1.44
I_6	14	17	11	18	140	109	1.15
LSD (P = 0.05)	2	1	2	5	16	11	0.13

[1] DAS = days after sowing.

[2] I_1 - 0.07 irrigation water/cumulative pan evaporation (IW/CPE) at all stages; I_2 - 0.03 IW/CPE at vegetative stage and 0.7 at flowering stage; I_3 - 0.7 IW/CPE at vegetative and podding stages and no irrigation at flowering stage; I_4 - 0.7 IW/CPE at vegetative and flowering stages and 0.3 at podding stage; I_5 - 0.5 IW/CPE at vegetative and podding stages and 0.7 at flowering stage; and I_6 - 0.5 IW/CPE at all stages.

Source: Pandey et al. (1995).

The effect of excess moisture or waterlogging could be direct by reducing - O_2 concentration in the rhizosphere or indirect by reducing availability of photosynthates. Waterlogging affects BNF due to anoxia. Singh et al. (1988) noted that flooding decreased leaf area index (LAI), nodulation, and seed yield of mung bean. Plants at seedling stage were more susceptible to flooding than those at flowering stage. Rainy season legumes, particularly short-season pigeonpea grown in sequence with wheat, do experience excess moisture conditions during early stages of their growth and consequently suffer loss of plant stand resulting in low productivity. It is therefore imperative to provide appropriate drainage (surface or subsurface) especially in low lying areas. Raised bed and ridge-furrow seed beds are quite effective in draining out the excess water, ensure better plant stand, and enhance yield of legumes.

Weed Management

In early stages of crop growth, legumes are poor competitors to weeds and consequently suffer heavy yield losses. Studies under the AICPIP during 1983-85 revealed yield losses (due to unchecked weeds) of 0.65 t ha^{-1} (44%) in pigeonpea, 0.29 t ha^{-1} (36%) in mung bean, 0.62 t ha^{-1} (50%) in black gram, and 0.78 t ha^{-1} (42%) in chickpea over weed-free plots (Table 15).

Table 15: Effect of weed control measures on productivity of grain legumes under rainfed conditions during 1983-1985.[1]

Treatment	Grain yield (t ha^{-1}) Pigeonpea (9)[2]	Mung bean (15)	Black gram (12)	Chickpea (18)
Weedy control	0.81	0.52	0.64	1.04
Weed free	1.46	0.81	126	1.82
One hand weeding (25-30 days after sowing)	1.17	0.71	0.98	1.34
One intercultivation	1.04	0.64	0.81	NT[3]
Fluchloralin (1.0 kg ha^{-1})	1.13	0.79	0.93	1.43
Pendimethalin (0.75 kg ha^{-1})	1.21	0.76	0.91	NT
Oxadiazon (0.75 kg ha^{-1})	1.19	0.77	0.91	1.23
Yield loss due to weeds (%)	44	36	50	42

[1]A11 India Coordinated Pulses Improvement Project trials.
[2]Figures in parentheses denote number of locations.
[3]NT = not tested.

The nature and magnitude of crop-weed competition is influenced by several factors such as crop species, cropping system, planting time, plant population, moisture availability, and fertility conditions. Since weeds compete with crop plants for moisture, nutrients, light, and space, their adverse effect on BNF is obvious.

Among various management practices, pre-emergence application of pendimethalin at 1.0-1.5 kg ha^{-1} and metolachlor at 1.0-1.5 kg ha^{-1}, and pre-plant incorporation of 1.0 kg ha^{-1} fluchloralin were effective in controlling seasonal weeds in chickpea, lentil, pea, common bean, pigeonpea, black gram, and mung bean in northern India (Ali 1994b). Adverse effects of high doses of herbicides on plant growth, yield, and nodulation in legumes have also been observed (Goyal et al. 1991). In a field experiment at Faizabad, Uttar Pradesh, Vaishya et al. (1995) studied relative efficacy of cultural and chemical methods of weed management in chickpea. They found that use of herbicide (1.0 kg ha^{-1} fluchloralin) appreciably decreased number of nodules as compared with the weedy check and hand weeding (Table 16). The grain yield was, however, significantly high with herbicide use due to control of weeds. Sandhu et al. (1991) at Ludhiana, Punjab, India also found that number of nodules, dry weight of nodules, and nitrogenase activity in chickpea decreased with application of herbicides (oxyfluorfen, linuron, oxadiazon, and metribuzin) as compared with hand weeding.

Table 16: Effect of weed management practices on nodulation and yield of chickpea at Faizabad in Uttar Pradesh, India during 1987/88.

Weed control measure	Nodules (number $plant^{-1}$)	Grain yield ($t\ ha^{-1}$)
Hand weeding (25 and 45 DAS)[1]	27.3	2.20
Fluchloralin(1.0 kg ha^{-1})	17.0	1.72
Fluchloralin (1.0 kg ha^{-1}) and hand weeding at 20 DAS	20.3	1.67
Weedy control	24.0	1.16
LSD (P = 0.05)	1.6	0.10

[1] DAS = days after sowing.

Source: Vaishya et al. (1995).

Intercropping of short-statured legumes such as black gram, mung bean, cowpea, and soybean helps in smothering weeds and enhancing crop productivity (Ahlawat and Venkateshwarlu 1987; Ali 1988). Among various legumes, cowpea has been found to be more efficient in smothering weeds, followed by mung bean and soybean. It would, therefore, be imperative to grow dense canopy legumes both as sole crops and intercrops to suppress weeds besides improving physical and biological conditions of soil and high economic returns.

FUTURE RESEARCH PRIORITIES

Even though legumes have a major role to play in the N cycle of rice-wheat cropping systems (RWCS), their primary purpose for cultivation is for grain. Good conditions for crop growth are required for both optimal fixation of N_2 and grain yield. Most of the agronomic and genotypic improvements for legumes in the past have been done for optimal growing conditions. Introduction of legumes in RWCS would be an opportunity cropping, largely under conditions of unfavourable soil moisture, soil texture, nutrients, and weather. There is a need to develop genotypes and agronomic practices to overcome constraints faced by the genotypes to reduce the opportunity costs involved in this cropping.

Development of simulation models would allow identification of crop characteristics that are needed to optimize resource utilization in RWCS. Already simulation models of most legumes, e.g., groundnut, soybean, and chickpea, that can be potentially used in such systems have been developed. But there is an urgent need to develop these models for other legumes. However, adequate simulation of N_2-fixation, especially under adverse conditons is still unsuccessful. Successful simulation of crop growth and N_2-fixation would permit better conceptualization of constraints and opportunities for growing legumes in RWCS.

More multilocational testing of agronomic packages of legumes with critical observation should be done as soil conditions for the rice-wheat systems vary greatly from location to location. These would allow validation of models and permit generalizations that may be useful for other locations with different environmental conditions.

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7

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] Averageof 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

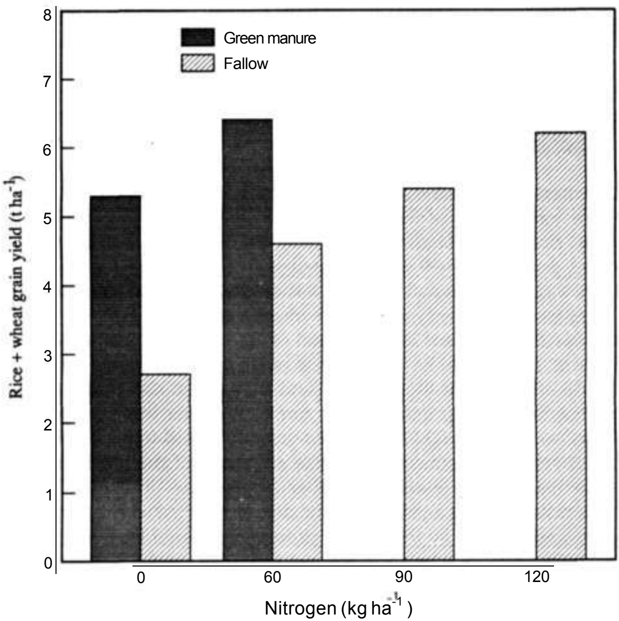

Figure 1: Effect of green manuring and fertilizer nitrogen (N) on rice + wheat yields and N economy in rice-wheat system.
(Source: Beri and Meelu 1981).

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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Prospects of Legumes in Rice and Wheat Cropping Systems

8

Overview and Prospects for Enhancing Residual Benefits of Legumes in Rice and Wheat Cropping Systems in Bangladesh

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ABSTRACT

The paper gives an overview of the current status of research in Bangladesh and focuses on enhancing productivity of rice-wheat systems by including a legume crop in rice-wheat rotations. It starts with description of a range of pulse crops that farmers can grow without affecting the yield of main cereal staples, but at the same time producing an extra benefit of using less fertilizer nitrogen and improving soil health in general. The paper identifies several niches for expansion of pulse crops for different soil and land type situations. Results of ongoing experiments on residual benefits of legumes on succeeding crops have been summarized. Growing of green manure legumes as a break crop between two cereals has been identified as one of the most promising avenues for economy on the use of fertilizer nitrogen. On-farm experiments conducted in different locations demonstrated the beneficial effect of pulse crops such as mung bean, cowpea, and chickpea on the yield of succeeding rice and wheat crops. Mixed cropping of wheat at different proportions with lentil and chickpea has been identified as a promising way for expansion of pulses cultivation in the country. Potential *Rhizobium* strains that could increase yields of lentil, chickpea, cowpea, groundnut, mung bean, and soybean have been identified. The paper finally identifies areas where there is further scope for concentrating research to develop varieties and management practices for efficient utilization of available techno-economic niches to integrate legumes in rice-wheat rotations.

INTRODUCTION

Pulses are important components in crop production systems of Bangladesh agriculture. Many different types of pulse crops such as khesari *(Lathyrus sativus),* lentil *(Lens culinaris),* chickpea *(Cicer arietinum),* black gram *(Vigna*

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mungo), mung bean *(Vigna radiata),* cowpea *(Vigna unguiculata),* and pea *(Pisum sativum)* are grown in Bangladesh. Farmers grow them mostly under rainfed conditions in cropping systems that can accommodate rice *(Oryza sativa)* and wheat *(Triticum aestivum).* The major pulses such as khesari, lentil, chickpea, and pea are traditionally grown during the dry winter months *{rabi* season) under rainfed conditions. These contribute more than 80% to pulses production. Black gram and mung bean are grown in late *kharif* as well as early summer (January-April) and pigeonpea can be grown during *kharif* (rainy season, April-October) and *rabi* (post-rainy season, November-April). Most of the area under pulses is concentrated in the greater districts of Faridpur, Jessore, Barisal, Rajshahi, Kushtia, Patuakhali, Noakhali, Bhola, Pabna, and Chittagong. Pulses occupy about 0.71 million ha and produce about 0.53 million t of grain annually (Table 1) as against an estimated requirement of 1.8 million t.

Table 1: Area, production, yield, and season of cultivation of major pulses in Bangladesh during 1993/94.

Crop	Area ('000 ha)	Production ('000 t)	Yield (kg ha^{-1})	Season of cultivation
Khesari	245.8	185.3	755	*Rabi*
Lentil	207.5	167.3	806	*Rabi*
Chickpea	85.6	61.5	719	*Rabi*
Black gram	67.1	52.1	775	*Kharif*
Mung bean	53.7	30.3	562	*Kharif*
Other pulses[1]	49.9	30.6	613	*Kharif/Rabi*
Total (Pulses)	709.6	527.1	743	

[1] Cowpea,pigeonpea, faba bean, and horse gram.

Source: BBS (1994).

With the advent of high-yielding cereals production technology, the area under pulse crops is gradually declining. Cultivation of only high-yielding cereals has resulted in a faster rate of depletion of soil fertility because much more nutrients are removed from the soil with the harvested crop than are added through inorganic fertilizer, which remains the chief source of replenishment of soil plant nutrients. This has been reflected in leveling-off of rice and wheat yields and even decline in some major production areas. Continuous cereal cropping has depleted inherent soil fertility (organic matter) resulting in deficiencies of important plant nutrients. The average organic matter content decreased from 1.21% in 1969/70 to 0.98% in 1989/90 in the High Ganges River Floodplain and from 1.45% in 1969/70 to 1.15% in 1989/90 in the Barind Tract (Miah and Karim 1995). The full potential of modern cultivars of rice and wheat cannot be sustained on a long-term basis without focusing attention on the wider range of potential nutrient deficiencies. The availability of balanced nutrients at appropriate levels is crucial to realize the full potential of modern cultivars of rice and wheat. Grain legumes have a considerable manuring value in improving rice or wheat productivity.

The Bangladesh Agricultural Research Institute (BARI) develops technologies to incorporate pulse crops in rice-wheat systems so as to halt their yield decline and to produce additional pulses by increasing the cropping intensity. Different pulses are suited to different ecosystems. Due consideration is also given to crop diversification to increase the production and consumption of pulses. These efforts have opened up possibilities for expanding pulse cultivation in non-traditional areas.

This paper reviews research progress made on residual benefits of legumes, and future needs and prospects of pulses in rice-wheat cropping systems (RWCS) in Bangladesh.

PULSES IN THE CROPPING SYSTEM

Pulse crops are important components in the traditional cropping systems as well as in improved cropping systems in different agroecological zones (AEZs) of Bangladesh (Fig. 1). The existing cropping patterns match with the prevailing agroecological conditions of these zones. Some expansion of pulses without affecting other components of existing patterns has been made (Fig. 2). Out of a total 30 AEZs, pulse crops occur in the existing pattern in at least 8 AEZs namely AEZs 10,11,13,14,15,18,19, and 26 (Fig. 1).

The need to grow legume crops for replenishing soil fertility and improving organic matter content is well-recognized, yet farmers in many areas grow rice after rice in quest of producing enough food grains. This trend is particularly noticeable under an irrigated system where the sequence is mostly transplanted (T) *aman* rice (rainfed lowland rice grown in monsoon during August-November) followed by *boro* rice (winter rice grown under irrigated condition during January-May) or wheat.

Khesari

Khesari is cultivated as a relay crop with T *aman* rice in the medium lowlands and lowlands as a second season crop in clay soils which remain wet for a long time. It can withstand short drought spells and moderate soil salinity. The seed is broadcast on the saturated soil 15-20 days before rice is harvested.

In view of the importance of the crop, BARI launched a breeding program to develop low neurotoxin, high-yielding varieties suitable for existing cropping systems. Two low-toxin varieties Barikheshari-1 and Barikheshari-2 have been developed and are under cultivation in farmers' fields.

Lentil

Lentil is usually grown in *aus* rice (upland direct-seeded rice grown in summer during April-July)-fallow-lentil and jute (*Corchorus olitorius, C. capsularis)*-

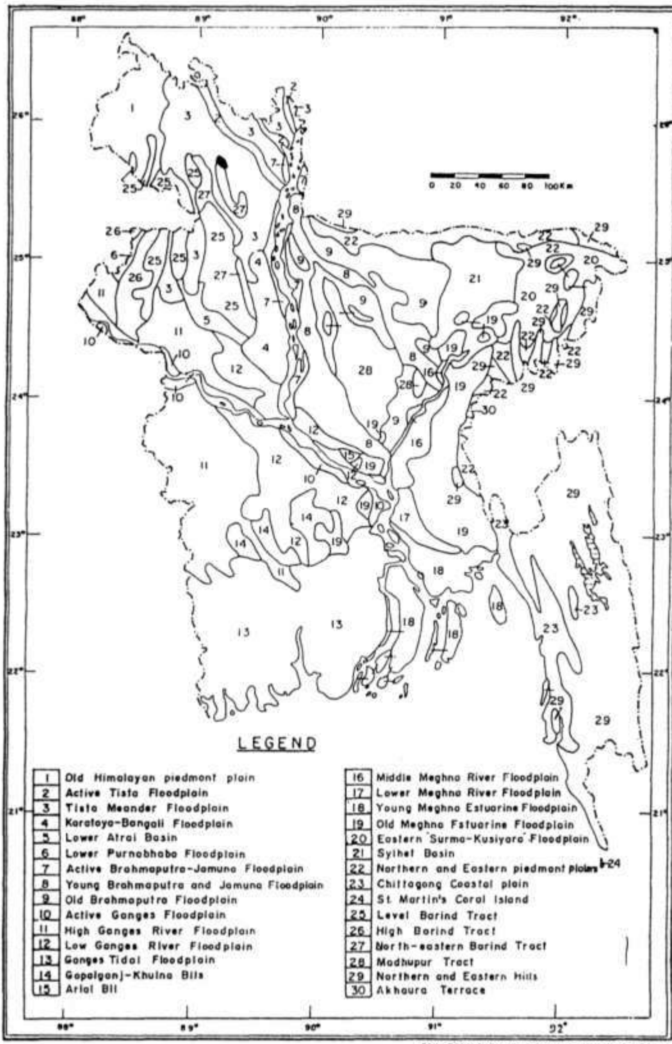

Figure 1: Agroecological zones of Bangladesh.

Month: 3 4 5 6 7 8 9 10 11 12 1 2 3

Pulse crop.	Cropping pattern			Area
Khesari	*Aus* + B *aman* rice	Khesari		Widespread
	T *aman* rice	Khesari		Widespread
Lentil	*Aus* rice	Fallow	Lentil	Widespread
	B *aman* and/or T *aman* rice	Lentil		Widespread in deep water *aman* areas
Chickpea	*Aus* rice	Fallow	Chickpea	Widespread
	B *aman* and /or T *aman* rice	Chickpea		Late planting
	Fallow	Short-duration *aman* rice	Chickpea	Barind region
Black gram	*Aus* rice	Black gram	Fallow	Widespread
	Aus rice	Black gram	Wheat / sugarcane	Widespread in northern districts
Mung bean	T *aus* rice	T *aman* rice	Mung bean	Widespread
	Aus rice	Mung bean	Fallow	Southern region
	Mung bean	T *aman* rice	Winter crops	Southern region
Cowpea	Dibbling *aus* rice	T *aman rice*	Cowpea	Southern region

Figure 2: Rice-based cropping patterns involving major pulses in Bangladesh during the year from March (dotted lines indicate relay cropping; B = broadcast; T = transplanted).

fallow-lentil cropping patterns. It is often grown with mustard *(Brassica campestris)* as a mixed crop and relay crop by broadcasting lentil seeds directly in the standing broadcast *aman* rice (lowland direct-seeded rice grown in summer during April-November) about 2-3 weeks before harvest. This practice enables better and early establishment of lentil seedlings because of an adequate supply of surface moisture which otherwise tends to be quickly lost once the rice has been harvested. The local cultivar suffers from rust *(Uromyces fabae)* and Stemphylium blight *(Stemphylium* spp). Efforts are being continued at BARI to develop high-yielding, disease-resistant varieties so that the area and production can be increased within the existing cropping systems. Four early-maturing varieties, Utfala, Barimasur-2,Barimasur-3, and Barimasur-4 have been released. These can easily be fitted into farmers' cropping patterns.

Chickpea

Chickpea is grown on well-drained, sandy loam alluvial to clay loam soil under *aus* rice /jute-chickpea or T *aman* rice-chickpea cropping patterns. In the first pattern, the previous crop of paddy or jute is harvested by August and the land remains vacant until chickpea is sown in early November at the appropriate time without difficulty. In the second pattern where chickpea has to follow T *aman* rice, sowing is delayed until late November or early December depending on harvest time of rice. Most of the area of chickpea is now concentrated within the Gangetic floodplain. However, yield stability is very low due to susceptibility to diseases including dry root rot *(Rhizoctonia bataticola),* collar rot *(Sclerotium rolfsii),* and Botrytis gray mold *(Botrytis cinerea).* Recently, five varieties, Barichhola 2, Barichhola-3, Barichhola-4, Barichhola-5, and Barichhola-6 resistant to Fusarium wilt were released.

Mung bean

Mung bean is traditionally cultivated in winter. Recently, however, there is an interest in cultivating it in summer to boost pulse production. About 65-70% of total mung bean cultivated is grown in a stable *aman* rice (July-December)-mung bean (January-February/March/April)-*aus* rice (April-July/August) cropping pattern. These cultivars are green-seeded, photoperiod-insensitive types. The remaining mung bean is cultivated in other parts of the country mainly in the *aus* rice-mung bean-fallow cropping patterns. These cultivars are golden-seeded, photoperiod-sensitive, and long-duration types. However, the area under this cropping pattern is being replaced by other winter crops such as wheat and mustard. Three short-duration varieties, Kanti, Barimung-3, and Barimung-4 of 65-70 days duration have been released for commercial cultivation. These varieties can fit well in RWCS.

Black gram

Black gram is sown in August/September in well-drained medium highlands or highlands after the harvest of *aus* rice in *aus* rice-black gram-fallow/ wheat cropping pattern. Local cultivars are photoperiod-sensitive and susceptible to yellow mosaic virus (YMV) and powdery mildew. Three short-duration, YMV-tolerant varieties, Barimash-1, Barimash-2, and Barimash-3 have been released by BARI. These varieties produce 20-30% higher yield than the local control, and also fit well into the fallow period of the *aus* rice-*fallow-rabi* crops cropping pattern provided sowing is completed in August. Long-duration varieties (85-95 days) are grown in the *aus* rice-black gram-fallow cropping pattern. Some farmers grow this crop in October/November in the char (newly accreted) land after the recession of flood water. It is also grown under zero tillage condition on the roadside.

Pigeonpea

Pigeonpea is a minor pulse crop in Bangladesh, grown on about 6000 ha. The production of 4200 t contributes only 0.8% of the total pulses production. Pigeonpea being a long-duration crop does not fit into annual rotations with other crops. Tall, long-duration (300 days) varieties are grown along the roadside and in backyards. Pigeonpea is grown as a mixed crop with upland rice, and finger millet *(Eleusine coracana)* in small pockets of Meherpur, Kustia, Jessore, Pabna, Rajshahi, and Jamalpur districts. It is also grown as a fuel crop and to a limited extent on field boundaries. Pigeonpea area extends northwards in the Active Tista Floodplain (AEZ-2) and Tista Meander Floodplain (AEZ-3).

Cowpea

Cowpea is mostly grown in Chittagong, Chittagong Hill Tracts, and southern parts of Noakhali and Laximpur districts. It is also grown in Barisal and Patuakhali districts. In Chittagong and Noakhali, it is sown during the end of November until mid-January in a T *aman* rice-cowpea cropping pattern. Some farmers practice dibbling *aus* rice relayed with cowpea. The local cultivars are long-duration types (130 days) and are indeterminate in habit. Two varieties, Barifalon-1 and Barifalon-2, have been released for cultivation.

PRODUCTION POTENTIAL AND RESIDUAL BENEFIT OF GRAIN LEGUMES IN RICE-WHEAT CROPPING SYSTEMS

Research conducted at different locations in Bangladesh has demonstrated that productivity of rice-wheat cropping can be increased by including a legume crop in rice-wheat rotations. With the availability of new varieties of pulses, it has now become possible to fit them into different cropping sequences.

In a cropping systems trial' where the preceeding crops were summer pulses, grain yield of mustard increased by 3-4% and that of wheat by 10-23% compared with fallow (Table 2). This suggests that the nitrogen (N) added to soil by summer pulses benefited succeeding mustard and wheat crops. Highest gross return (Tk 36865-40130 ha"^{1}) and beneht.cost ratio (2.90-3.34) were observed in the patterns involving black gram variety MAK 1 and mung bean variety Kanti (BARI1990). On-farm research conducted in wheat-mung bean-T *aman* system established that through judicious and balanced application of N, phosphorus (P), potassium (K), sulfur (S), and zinc (Zn) to wheat crop and inclusion of a leguminous crop (mung bean), a yield level of about 5 t ha^{-1} of T *aman* rice could be sustained even up to the 9th cropping (BARI 1990).

Six cropping patterns were tested at Ishurdi during 1987 and 1988 against the existing cropping pattern *(aus* rice-fallow-wheat or mustard or lentil). *Aus* rice was cultivated using farmers' practice; after the harvest of *aus* rice to ground level, mung bean and black gram were sown under minimum tillage conditions. Three post-rainy season crops, wheat, mustard, and lentil, were grown after mung bean and black gram. The residual benefit of incorporating a pulse crop was prominent in the cropping patterns *aus* rice-mung bean-mustard and *aus* rice-black gram-mustard (Table 3) (BARI 1990, 1991).

Kar and Musa (1990) reported that in the Barind region *rabi* crops such as chickpea, lentil, mustard, and linseed *(Linum usitatissimum)* planted immediately after the harvest of rice in October can produce reasonable yields. The key lies in utilizing the residual soil moisture for good crop growth (Razzaque et al. 1992). Mixtures of *rabi* crops following T *aman* rice were successfully demonstrated in the Barind Tract. A good example is a mixture of the chickpea and barley *(Hordeum vulgare);* the average yield of chickpea was 1 t ha^{-1} over a period of three years during 1981-83 (Raisuddin and Nur-E-Elahi 1984). This cropping system gave more than double the net return of traditional systems such as fallow-T *aman* rice-fallow and local *aus* rice-T *aman* rice-fallow.

Beneficial effects of legumes on succeeding cereal crops in terms of increase in yield have been reported by many researchers in Bangladesh. Such benefits are probably due to N_2-fixation from the atmosphere which reduces the need for application of N fertilizers. Biological nitrogen fixation (BNF) was estimated at 75 kg N ha^{-1} in lentil, 35-87 kg N ha^{-1} in chickpea, and 58-192 kg N ha^{-1} in groundnut (Sattar et al. 1994).

Patwary et al. (1989) observed that rotations, particularly those including legumes, built up the N status of the soil although the net gain differed among crop sequences (Table 4). The maximum net gain in total N (50 kg ha^{-1}) was obtained with winter soybean *(Glycine max)-rainy* season rice-autumn rice sequence followed by wheat-mung bean-autumn rice (38 kg ha^{-1}) and soybean-jute-autumn rice (27 kg ha^{-1}). The mean value of total N

Table 2: Agroeconomic performance of different cropping systems at Kalikapur, Ishurdi, Pabna, Bangladesh, 1989/90.

Cropping systems[1]	Grain yield ($t\ ha^{-1}$)			Gross return ($Tk\ ha^{-1}$)	Total variable cost ($Tk\ ha^{-1}$)	RAVC[2] ($Tk\ ha^{-1}$)	Benefit:cost ratio
	Crop1	Crop2	Crop3				
Rice-fallow-lentil (F1)	1.30	–	1.24	28315	9925	18390	2.85
Rice-BG 1-lentil (F2)	1.30	0.61	1.16	33880	11413	22467	2.97
Rice-BG 2-lentil (FA)	1.30	1.11	1.11	38135	11413	26722	3.34
Rice-MB-lentil (FA)	1.30	0.82	1.14	34380	11413	22967	3.01
Rice-fallow-mustard (F1)	1.30	–	0.95	24535	11209	13326	2.19
Rice-BG 1-mustard (F2)	1.30	0.61	0.99	31835	12697	19138	2.51
Rice-BG 2-mustard (FA)	1.30	1.11	0.98	36865	12697	24168	2.90
Rice-MB-mustard (FA)	1.30	0.82	0.99	32815	12697	20118	2.58
Rice-fallow-wheat (F1)	1.30	–	2.08	24755	12047	12708	2.05
Rice-BG 2-wheat (F2)	1.30	0.61	2.29	33080	13535	19545	2.44
Rice-BG 2-wheat (FA)	1.30	1.11	2.56	40130	13535	26595	2.96
Rice-MB-wheat (FA)	1.30	0.82	2.46	35155	13535	21620	2.60

[1]Rice-fallow/summer pulse (black gram, mung bean)-*rabi* crops (lentil, mustard, wheat) cropping pattern; F1 and F2 = existing cropping systems used by farmers; FA = alternative cropping systems; rice = broadcast *aus* (upland direct-seeded rice grown in summer); BG 1 = local black gram variety Katikalai; BG 2 = black gram variety MAK 1; MB = mung bean (variety Kanti).

[2]RAVC = Return above variable cost; US$ 1 = 42.50 Taka (Tk).

Source: BARI (1990).

Table 3: Yield increase over existing cropping pattern, net return, and benefit:cost ratio of rice-based cropping pattern at Ishurdi, Pabna, Bangladesh during 1987/88.

Cropping pattern tested	Yield increase (%)		Net return increase (%)		Benefit : cost ratio		Change in yield of last crop in a sequence (kg ha^{-1})	
	1987	1988	1987	1988	1987	1988	1987	1988
Aus rice-mung bean-wheat	15	17	62	131	1.04	1.05	–354	–77
Aus rice-mung bean-mustard	36	34	101	139	1.15	1.16	+52	+50
Aus rice-mung bean-lentil	32	30	63	78	1.64	1.91	–6	–39
Aus rice-black gram-wheat	19	19	90	123	1.16	1.01	–312	–110
Aus rice-black gram-mustard	46	44	133	146	1.33	1.19	+115	+132
Aus rice-black gram-lentil	37	29	74	53	1.79	1.90	–49	–166

Source: BARI (1990, 1991).

Table 4: Soil N content (kg ha^{-1}) as influenced by different sequential cropping systems in Old Brahmaputra Alluvium Soil, Bangladesh, 1987–89.

Cropping sequence[1]	Fertilizer treatment[2]	Total N added in two years	Total N removed in two years	N status after two years[3]	Change in total soil N
F-F-AR	F1	180	148	1774	+15
	F2	135	110	1772	+13
	F3	90	72	1766	+7
	Mean	135	110	1771	+12
F-J-AR	F1	320	166	1744	–15
	F2	240	132	1718	–41
	F3	160	118	1693	–66
	Mean	240	136	1718	–41
S-J-AR	F1	360	370	1808	+49
	F2	270	285	1783	+24
	F3	180	218	1767	+8
	Mean	270	291	1786	+27
S-RSR-AR (one year)	F1	200	230	1853	+94
	F2	150	171	1800	+41
	F3	100	137	1775	+16
	Mean	150	176	1809	+50
W-Mu-AR (one year)	F1	210	211	1823	+64
	F2	157	173	1790	+31
	F3	105	122	1778	+19
	Mean	157	168	1797	+38

(Contd.)

Table 4 (*Contd.*)

Cropping sequence[1]	Fertilizer treatment[2]	Total N added in two years	Total N removed in two years	N status after two years[3]	Change in total soil N
W-F-AR					
	F1	380	250	1750	–9
	F2	285	206	1740	–19
	F3	190	106	1729	–30
	Mean	285	187	1740	–19

[1]F = fallow; AR = autumn rice; J = jute; S = soybean; RSR = rainy season rice; W = wheat; Mu = mung bean.
[2]F1= 100% of recommended dose; F2 = 75% of recommended dose; F3 = 50% of recommended dose. 100% recommended dose of N (kg ha^{-1}) for each crop: wheat = 100, rice = 90, mung bean = 20, and soybean = 20.
[3]Initial N status of soil was 1759 kg ha^{-1}.
Source: Patwary et al. (1989).

in soil showed a deficit balance of 41 kg N ha^{-1} in fallow-jute-autumn rice and 19 kg N ha^{-1} in wheat-fallow-autumn rice sequence. Total N uptake by the crops having legumes in their cropping sequence was higher than total fertilizer added showing the contribution of legumes to the system by N_2-fixation. The total yield of grain and straw of rice increased by about 12% following chickpea and 8% following lentil in relation to rice following wheat although the difference was not significant (Table 5). In a two-year study during early rainy season Quayyum et al. (1994) evaluated the effect of preceding crop and crop combinations and N levels on growth and nutrient uptake of rice. Rice sown after sole black gram had tallest plants (94.8 cm), higher dry matter (1.26 kg m^{-2}), and higher leaf area index (1.87) than when sown after early rainy season (March-April) *aus* rice and maize *(Zea mays)* alone (Table 6). Nitrogen content in rice at all the growth stages was significantly higher when it followed black gram as sole crop and intercrop with maize than that in other cropping patterns. A similar trend was noticed for nutrient contents in grain and straw, and nutrient uptake. The grain yield of rice was significantly higher when the crop was grown after sole black gram.

Table 5: Total yield, N content, and total N yield in grain and straw of rice as affected by preceding cereal and legume crops, Bangladesh Agricultural University farm, Mymensingh, Bangladesh.

	Total yield[1] (kg ha^{-1})		N content[2] (%)		Total N yield[2] (kg ha^{-1})	
Preceding crop	Grain	Straw	Grain	Straw	Grain	Straw
Chickpea	5272(12)	3466(12)	0.70a	0.36	36.78a	12.65
Lentil	5108 (8)	3363 (9)	0.71a	0.37	36.34a	13.38
Wheat	4721	3083	0.61b	0.36	28.82b	11.20
F-test[3]	NS	NS	*	NS		NS

[1]Figures in parentheses indicate increase (%) over preceding wheat crop.
[2]Means followed by same letter do not differ significantly at 5% level.
[3]NS = not significant; * significant difference at 5% level.
Source: Patwary et al. (1989).

Rahman (1994) reported that incorporating berseem *(Trifolium alexandrinum),* a forage crop, in between T *aman* and *boro* rice in post-monsoon (wet to dry period) increased the grain yield of succeeding *boro* rice by 7-18% and straw yield by 35% (Table 7). Residual fertility left after *boro* rice increased the grain yield of T *aman* rice by about 4-14% and straw yield by 2-9%.

NITROGEN ECONOMY THROUGH GREEN MANURING IN RICE-WHEAT CROPPING SYSTEMS

The use of green manuring in rice-wheat systems may help in sustaining the productivity of both crops and improving the fertility of the soil. In regions

Table 6: Effect of preceding crop, the crop combination, and nitrogen (N) level on crop growth attributes, and N content and uptake in grain and straw of rice, Joydebpur, Gazipur, Bangladesh during 1989 and 1990.[1]

	Growth attributes at harvest				N content(%)		N uptake (kg ha^{-1})		
Treatment[2]	Plant height (cm)	Dry matter (kg m^{-2})	Leaf area index	Grain yield (t ha^{-1})	Grain	Straw	Grain	Straw	Total
Main plot (cropping pattern)									
T1	91.38	1.16	1.65	3.51	1.08	0.50	37.93	16.99	54.92
T2	92.15	1.15	1.69	3.56	1.11	0.53	39.53	18.34	57.87
T3	94.80	1.26	1.87	3.92	1.21	0.73	47.50	28.72	76.22
T4	91.39	1.15	1.67	3.43	1.06	0.47	36.52	15.65	52.17
T5	94.21	1.25	1.81	3.86	1.18	0.68	45.61	26.38	71.99
T6	93.60	1.24	1.77	3.65	1.15	0.65	41.99	24.28	66.27
T7	93.53	1.23	1.75	3.69	1.13	0.63	41.94	23.50	65.43
T8	94.01	1.24	1.76	3.74	1.16	0.60	43.39	24.73	68.12
CD ($P = 0.05$)	1.30	0.07	0.03	0.04	0.05	0.04	1.42	1.44	1.40
CV (%)	1.62	1.15	1.11	1.62	2.97	1.85	2.37	2.28	2.36
Sub-plot (N kg ha^{-1})									
N_0	86.67	1.08	1.46	2.85	1.01	0.38	28.95	10.13	39.08
N_{40}	91.93	1.16	1.74	3.52	1.11	0.63	39.21	22.35	61.56
N_{80}	95.37	1.28	1.85	4.11	1.18	0.73	48.76	28.90	77.66
N_{120}	98.51	1.33	1.94	4.22	1.24	0.79	52.33	33.58	85.91
CD ($P = 0.05$)	0.82	0.06	0.02	0.03	0.02	0.03	1.15	1.35	1.38
CV (%)	1.51	1.12	1.08	1.58	2.58	1.50	2.29	2.19	2.25

[1]Pooled data.

[2]T1 = broadcast sole early rainy season rice (periodically fixed-maturity rice variety grown in March–April); T2 = row-seeded sole early rainy season rice; T3 = row-seeded sole black gram; T4 = uniform sole maize; T5 = maize in paired rows (100%) + black gram rows (33%); T6 = row-seeded early rainy season rice (67%) + prickly sesban (*Sesbania cannabina*); T7 = row-seeded early rainy season rice (100% + prickly sesban broadcast) (50%); and T8 = row-seeded early rainy season rice (67%) + black gram in rows (33%).

Source: Quayyum et al. (1994).

Table 7: Effect of forage crops on grain and straw yield (kg ha^{-1}) of *boro* rice under partially irrigated condition, BARI, Jamalpur, Bangladesh, 1990/91.

Cropping system[1]	Grain yield[2] (kg ha^{-1})	Straw yield[2] (kg ha^{-1})
TR-GP-BR/SB	5157 (15)	6032 (26)
TR-GP+BS-BR/SB	5313 (18)	6227 (30)
TR-MD+MZ-BR/SB	5154 (14)	5391 (13)
TR-SN+CP-BR/SB	4864 (8)	5748 (20)
TR-BS-BR/SB	5324 (18)	6484 (35)
TR-OT+BS-BR/SB	4828 (7)	5382 (12)
TR-F-BR (Control)	4500	4791

[1]GP = grass pea (khesari); BS = berseem; MD = mustard; MZ = maize; SB = *Sesbania rostrata;* SN = sunn hemp; OT = oat; CP = cowpea; BR = *boro* rice; TR = transplanted *aman* rice; and F = fallow.

[2]Mean of two years; figures in parentheses indicate increase (%) over rice-rice.

Source: Rahman (1994).

where double cropping is practiced, summer green manuring can be introduced provided irrigation facilities are available. Productivity of all the major crop sequences such as rice-rice and rice-wheat increased when a green manure crop was introduced in *kharif* during April-June. Green manure may not be a substitute for chemical fertilizer but it can easily supplement a part of the fertilizer nutrient.

The experiments conducted in Bangladesh showed that *Sesbania* as a green manure could be a substantial supplementary source of N, especially for coarse-textured soils where large leaching losses of N from applied urea may occur (Bhuiyan 1992). This is particularly true for *boro* rice-fallow-T *aman* rice and wheat-fallow-T *aman* rice patterns where the fallow period during *kharif* could be properly used for green manure crops. Application of organic manures such as shoots of young cowpea and dhaincha *(Sesbania aculeata),* rice straw, and decomposed cow dung increased the yield of rice. The effectiveness of organic residues was in the order of cowpea > dhaincha > *Azolla* > decomposed cow dung > compost (BRRI1985).

Islam et al. (1990) observed that green manuring reduces fertilizer N by 25% in green manure crop-T *aman* rice-chickpea cropping pattern. Growing a green manure crop between *boro* rice and T *aman* rice crop helps to increase rice production and is better than keeping the land fallow (BRRI 1986).

A long-term field trial indicated that there was a cost-saving equivalent of 70 kg N ha^{-1} yr^{-1} in addition to long-term benefits accrued by green manuring in a *boro* rice-fallow-T *aman* rice pattern (BRRI 1990; Ahmed 1992). Bhuiyan (1992) and BRRI (1985) found that N fertilizer at a low rate (60 kg ha^{-1}) along with *Sesbania* proved to be the best treatment for the first crop.

In another long-term cropping system trial at the Bangladesh Rice Research Institute (BRRI), Ahmed (1992) reported that the average of four years of total rice yield per pattern was highest (9.3 t ha^{-1}) in the pattern *boro* rice-green manure-T *aman rice,* among the cropping patterns tested (Table 8). The lowest total rice yield (6.7 t ha^{-1}) was obtained from the wheat-T *aus* rice-T *aman* rice cropping pattern.

Table 8: Agronomic productivity of different crops in a long-term irrigated cropping pattern experiment at BRRI, Joydebpur, Bangladesh, 1984-87.

	Yield[1] (t ha^{-1})			Total yield[1] (t ha^{-1})		
Cropping pattern[2]	*Boro/rabi*	T *aus*/GM	T *aman*	Rice	Chickpea	Wheat
Improved pattern						
Boro rice-GM-T *aman* rice (BR 3) (BR 4)	5.5	9.9	3.8	9.3		
Chickpea-T *aus* rice-T *aman* rice (BR 3) (BR 11)	0.5	4.1	3.8	7.9	0.5	
Wheat-T *aus* rice-T *aman* rice (BR 1) (BR 10)	2.6	2.9	3.8	6.7	-	2.6
Farmers' pattern						
Boro rice-fallow-T *aman* rice (BR 3) (Pajam)	4.8	-	3.5	8.3		

[1] Average of four years; average of three replications per year.

[2] *Boro* rice or *rabi* crop-GM or T *aus* rice-T *aman* rice; *bow* rice is winter rice grown under irrigation; T *aus* rice is transplanted summer rice grown during March-July under irrigation; T *aman* rice is transplanted rainfed rice grown in monsoon; *rabi* crops are chickpea and wheat; and GM = green manure crop (yield is fresh weight of phytomass *Sesbania exaltata).*

Source: Ahmed (1992).

Sukuruddin and Miah (1984) reported that incorporation of *Sesbania* before T *aman* rice (BR-11) at the North-Bangladesh Tubewell Project in Thakurgaon, reduced N requirement by 50% and P and K by almost 75%. Incorporation of *Sesbania* produced 2.0 t ha^{-1} more grain than the plots having no green manure. Similar yield advantage was also observed at the Ganges Kobadak Project (Ahmed 1992). Among the *Sesbania* species, *S. rostrata* has the potential of adding about 180 kg N ha^{-1} to the soil, if the 60-day old crop is incorporated into the soil as a green manure. Two other species *$. cannabina* and *S. aculeata* produce 140-150 kg N ha^{-1} (BRRI 1991). However, the yield response due to green manuring *(Sesbania)* was more pronounced in coarse-textured soil (BRRI 1990, 1991). On coarse-textured low fertility soils, where leaching loss of N is a problem, about 4.5 t ha^{-1} of T *aman* rice can be obtained without chemical N fertilizer if *Sesbania* sp. (60-day-old having a biomass of *5-6* t ha^{-1}) grown in situ is plowed down as green manure within five days before planting T *aman* rice.

In a field trial, *Sesbania* was grown in green manure-T *aman* rice (BR 11)-wheat cropping system. *Sesbania* alone or in combination with urea at 30, 60, and 90 kg N ha^{-1} was tested. *Sesbania* alone increased T *aman* rice yield significantly and addition of N did not result in additional grain yield at Rajshahi (Table 9) (Bhuiya et al. 1989).

Table 9: Effect of urea-N and green manure combinations on the grain yield of modern varieties of rice in green manure-rice and of wheat in green manure-rice-wheat cropping patterns, BRRJ Regional Station, Rajshahi and Comilla, Bangladesh, 1988.

	Rajshahi		Comilla		Rajshahi	
	T *aman* rice (BR 11) yield (t ha^{-1})		Rice yield (t ha^{-1})		Wheat (Kanchan) yield (t ha^{-1})	
Treatment[1]	Irrigated	Rainfed	*Boro (BR 3)*	T *aman* (BR 11)	Irrigated	Rainfed
Absolute control[2]	4.1b[3]	4.2b	2.2cd	2.4c	0.9d	0.5c
DH_0+N_0	4.4b	3.8b	2.5c	3.0bc	1.3c	0.7de
$DH+N_0$	5.6a	5.8a	1.9d	3.3abc	1.3c	0.8d
$DH+N_{30}$	6.0a	5.9a	2.7c	4.2ab	2.4b	1.1c
$DH+N_{60}$	5.9a	6.0a	4.0b	4.5a	3.1a	1.6b
$DH+N_{90}$	5.9a	6.4a	4.8a	4.3ab	3.3a	2.0a
CV (%)	5.5	6.0	10.9	11.8	8.2	8.9

[1]DH = dhaincha *(Sesbania aculeata);* subscripts denote urea-N rate in kg ha^{-1}).

[2]Commondose of P and K were not used.

[3]Means within column followed by same letters are not significantly different at the p = 0.05 level.

Source: Bhuiya et al. (1989).

Bhuiya et al. (1995) observed that incorporation of *Sesbania rostrata* 35 days after seeding resulted in a tremendous increase in N contribution for the succeeding rice varieties BR 11, BR 22, Kalizira, and Nizershail. The study showed that N application had no effect after incorporation of 105 t ha^{-1} green biomass. Attempts were made by Rahim et al. (1995) to find out the effect of green manure and reduced fertilizer application on *boro* rice-fallow-T *aman* rice cropping pattern in Bogra Farming Systems Research site. Different doses of chemical fertilizers were also evaluated with and without green manure crop in the above mentioned pattern. *Sesbania* was sown on 20 May after the harvest of *boro* rice and incorporated 55 days after sowing. Results demonstrated that application of only N fertilizer at 80 kg N ha^{-1} gave identical grain yield (5.6 t ha^{-1}) as that of the plot in which 25 t ha^{-1} green biomass was added.

Rahman (1995) reported that different rates of *Sesbania* (5-25 t ha^{-1}) added to the soil allowed reduction of N-fertilizer rates by 50% for cultivation of high-yielding varieties of T *aman* rice in the Barind tract. Bhuiya et al. (1989) observed that in green manure plots 40 kg N ha^{-1} was as effective as the recommended rate of 80 kg N ha^{-1} for producing similar grain yield of rice.

DUAL-PURPOSE LEGUME CROPS

Farmers usually remove legume residues after harvesting of pods and use them either as fuel or fodder. Incorporation of the residues could be as effective as green manuring in increasing the productivity of black gram-T *aman* rice cropping systems (Quayyum et al. 1994).

An experiment was conducted to study the effect of plowing mung bean plants after harvesting the pods under dry conditions during November. The post-rainy season crops, lentil (L5), mustard (Tori 7), and wheat (Kanchan) were sown 12 days after the mung bean stover was plowed down. Recommended doses of fertilizers were added during final land preparation. Mung bean residues increased the grain yield and seed size of all the crops probably due to the added green manure (Table 10). In contrast, low yields were obtained in all the post-rainy season crops where mung bean plants were harvested. This might be due to the loss of soil fertility and moisture.

Table 10: Effect of mung bean residues on the following post-rainy season crops in the *aus* rice-mung bean-post-rainy season crop sequence, Ishurdi, Bangladesh, 1986/87.

	Yield[1] ($t\ ha^{-1}$)		
Treatment	Lentil	Mustard	Wheat
Fallow (control)	0.76b	1.01b	1.36ab
Harvesting of mung bean plants	0.75b	0.89b	1.22b
Plowing down of mung bean plants	0.91a	1.26a	1.49a
F-test[2]	*	NS	

[1]Figures followed by same letters within a column are not significantly different at the p = 0.05 level.

[2]* Significant at P = 0.05 level; ** significant at P = 0.01 level; and NS = not significant.

Source: Aziz and Rahman (1991).

NICHES FOR EXPANSION OF PULSES IN CROPPING SYSTEMS

Vast areas of medium highlands and highlands in the northern parts of the country are left fallow after the harvest of *aus* rice or jute until the sowing of winter crops such as wheat, chickpea, and lentil. This period varies from mid-August to the first week of November and can be utilized for growing mung bean or black gram. Besides, there is some possibility for the cultivation of mung bean during summer (March/April), replacing the low-yielding *aus* rice. Black gram and mung bean were found to fit well into *aus* rice-black gram/mung bean-wheat cropping pattern. This pattern is suitable for light-textured soils in highlands or medium highlands with adequate drainage. If this pattern could be promoted, a large area (about 40,000 ha) could be brought under pulse cultivation in northern districts where soil fertility is below critical level. Appropriate management practices with the availability of high-yielding, short-duration, photoperiod-insensitive, and synchronous cultivars of mung bean and black gram having seed dormancy and resistance to biotic and abiotic stresses will be very effective in increasing the area and production of pulses.

On-farm research has established that green manure legume crops such as dhaincha or cowpea can be incorporated in cropping sequences in many areas such as Barind region, High Ganges River Floodplain, and Tista Meander Floodplain without affecting the main *aman* rice crop; this permits a 50% reduction in application of N-fertilizer to the succeeding rice crop. The overall intention of this approach is to boost crop productivity on a sustained basis without impairing the ecological balance.

In many rainfed areas after the harvest of T *aman* rice farmers leave their land fallow because of inadequate moisture to grow a second crop. If a supplemental irrigation is provided at a later growth stage of the rice crop in October, residual moisture is left in the soil which is sufficient for establishment and growing of pulse crops.

A promising area for expanding chickpea cultivation is the Barind Tract comprising parts of Rajshahi, Bogra, Rangpur, and Dinajpur districts in the northwest of the country where about 0.15 million ha of land remains fallow in winter after rice harvest. The major cropping pattern is fallow-T *aman* rice-fallow, where T *aman* rice is planted in June/July and harvested in November-December. The area receives low rainfall (1200-1500 mm). Trials on chickpea by BARI's On-farm Research Division (OFRD), Barind, Rajshahi indicate that chickpea yields exceeding 1 t ha^{-1} can be harvested with few additional inputs. In this area chickpea must be planted by early November to ensure high yield. For successful cropping, local long-duration cultivars of rice need to be replaced by short-duration varieties such as BR 1, BR 14, and IR 50 (Table 11). Farmers are encouraged to grow chickpea due to the promising performance of the crop. The highest yield of chickpea was 2.5 t ha^{-1} in some motivational blocks. The area under cultivation increased from about 100 ha in 1990 to 9000 ha in 1997. If this trend is maintained and even if only 10% of the Barind could be brought under chickpea cultivation it would double the country's production of this crop (Rahman et al. 1995).

Table 11: Grain yields of modern, short- long-duration transplanted *aman* rice varieties and *rabi* crops in *rice-rabi* (pulses or oilseeds) cropping pattern in Barind, Bangladesh.

Rice cultivar/	Grain yield (t ha^{-1})				Grain yield (t ha^{-1})		
Harvest date	1988	1989	Mean	Rabi crop	1988/89	1989/90	Mean
BR1	4.17	2.93	3.55	Chickpea	0.66	1.04	0.85
(11-25 Oct)				Lentil	0.31	0.30	0.31
				Mustard	0.55	0.50	0.53
				Linseed	0.31	0.44	0.38
BR 14	4.58	4.21	4.37	Chickpea	0.77	0.81	0.79
(23 Oct-7 Nov)				Lentil	0.21	0.45	0.33
				Mustard	0.46	0.76	0.61
				Linseed	0.38	0.70	0.54
BR 11	5.00	4.71	4.85	Chickpea	0.30	0.30	0.30
(7-23 Nov)				Lentil	0.14	0.43	0.29
				Mustard	0.22	0.32	0.27
				Linseed	0.21	0.52	0.37

Source: Kar and Musa (1990).

The expansion of pigeonpea cultivation depends on the introduction of new genotypes and fitting the crop in cropping systems. Development of medium- and short-duration varieties can be one way of promoting pigeonpea in traditional cropping systems. The long-duration pigeonpea crop is exposed to many biotic and abiotic stresses for a longer period which adversely affect the productivity of the crop. One of the existing cropping patterns in the northern part of the country is *aus* rice-black gram fallow. After the harvest of black gram farmers cannot grow any post-rainy season crop due to lack of optimum moisture level. Short-duration pigeonpea could be grown as a mixed crop with black gram in rows 60-cm apart along with broadcast black gram. Black gram is harvested in December when pigeonpea attains a height of 60 cm and begins to flower. Thus it does not affect the black gram yield. High-yielding, long-duration varieties can also be used as bund crops in traditional areas as well as in hill farming.

One possible approach to increase the yields of pulses is to make an overall improvement of legume-*Rhizobium* symbioses. Many laboratory, pot, and field studies carried out by research institutions have led to the screening and selection of several effective strains of *Rhizobium* and *Bradyrhizobium* for use as inoculants. The potential strains identified are DUM-16 and BINA-LT-18 for lentil, BINA-CP-2 for chickpea, BINA-COP-7 for cowpea, BAU-700 for groundnut *(Arachis hypogaea),* BINA-MB-1 for mung bean, and BAU-107 for soybean. It has been experimentally shown that pulse production can be increased from 20% to 94% by the use of biofertilizer (Miah and Karim 1995). High yields were obtained due to the combined effect of biofertilizer and an adequate dose of P, K, and S.

Demonstration trials were conducted in selected farmers' fields on the use of biofertilizers in cultivation of lentil, chickpea, cowpea, and groundnut. The yield increase due to application of biofertilizers in these crops ranged from 20% to 44% (Table 12). In the case of soybean, inoculation increased the yield by 94% over the control. Distinct beneficial effects of *Rhizobium* inoculation have been observed in khesari, lentil, and mung bean as indicated by nodule formation, nodule mass, shoot dry matter, and grain yield.

Table 12: Effect of *Rhizobium* biofertilizer on grain yield of legumes in Bangladesh.

Crop	Mean yield (kg ha^{-1})		Increase in yield
	Without biofertilizer	With biofertilizer	(%)
Lentil	730	950	30
Chickpea	693	985	42
Groundnut	1258	1660	32
Mung bean	638	878	38
Black gram	853	1024	20
Cowpea	715	1030	44
Soybean	815	1582	94

Source: Miah and Karim (1995).

RESEARCH NEED AND FUTURE STRATEGY

While research is underway to overcome the constraints to crop production, research programs should delve into issues likely to pose problems in the future. No substantially superior varieties of pulses are yet available. Information on production technology practices in general and location-specific systems-based in particular is still meager. The problem is how to make these pulse crops more competitive under rainfed conditions and with limited irrigation and fit them into farmers' existing cropping systems without displacing major food crops. Some of the research areas which need due attention are as follows:

- A varietal improvement program should focus on developing short-duration pulse varieties that fit in rice-wheat systems and can be grown as sequential, intercrop, or mixed crop for diverse agroclimatic situations. This would avoid major disruption in production of main food crops. Expansion of pigeonpea is possible if short- and medium-duration (100-120 days) varieties are developed for growing as mixed and intercrop with black gram in the pattern *aus* rice-black gram-fallow. Careful selection of species, genotype, and efficient management will lead to most beneficial systems. The improved varieties should also withstand both excess and limited soil moisture conditions.
- Appropriate varieties of T *aman* rice should be developed so that adjustments of existing cropping systems can be made to ensure timely planting of winter pulses.
- The long-term effect of cropping systems involving legumes on productivity, soil fertility, and diseases buildup in RWCS needs to be studied.
- Research should be conducted on integrated nutrient management including biofertilizers to exploit the yield potential of pulses in RWCS.
- Various systems options with legume crops which increase productivity, optimize nutrient cycling, and reduce pest infestation should be explored and exploited.
- In order to match crop needs and to avoid drought loss of crops, research should concentrate on technology generation for increased water use-efficiency. This includes development of tillage implements, tillage practices, and cultural operations.
- The need to sustain the productivity of RWCS is greater today than ever before. Cropping in the post-wheat period demands a wide range of legume cultivars and crops with extremely short-duration, combined with dual purpose use for income and green manure. Research should focus on cultigen selection and agronomic aspects for the cropping system.
- In-depth research on soil moisture relationships of the pulse-growing areas should be initiated to match cropping pattern with available soil moisture under purely rainfed and irrigated conditions.

- Technology packages for intercropping, relay cropping, and mixed cropping of pulses with cereals, oilseeds, and sugarcane *(Saccharum officinarum)* should be developed.
- Extension activities for promotion of green manure crops in intensive rice- and wheat-based cropping systems should be conducted.

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9

Overview and Prospects for Enhancing Residual Benefits of Legumes in Rice and Wheat Cropping Systems in Nepal

S.P. Pandey, S. Bhattarai, N.K. Rajbhandari, R.P. Sah, and R.P. Sapkota[1]

ABSTRACT

The grain legumes, lentil, khesari, chickpea, and pigeonpea, are commonly grown in rice-based cropping systems. Mung bean and cowpea are grown to some extent in rice-wheat cropping systems as catch crops or green manures. Dhaincha is grown for green manuring rice crop in rice-wheat systems.

The enhancement of residual benefits of legumes in rice-wheat systems depends largely on the quantity of legume biomass that can be returned back into the soil. A review of the available research information shows that green manure legumes significantly benefit the succeeding rice crop. The beneficial effects of grain legumes may be negligible due to the removal of most plant parts at harvesting. Additional research is needed for quantification of residual effects, identification of limiting factors (soil, environment, agronomic, and genetic), and evaluation of crop and soil management practices for increased legume nitrogen fixation.

INTRODUCTION

Legumes are very important crops in Nepal and rank fourth in area after rice *(Oryza sativa),* maize *(Zea mays),* and wheat *(Triticum aestivum).* They include winter legumes, mainly lentil *(Lens culinaris),* khesari *(Lathyrus sativus),* and chickpea *(Cicer arietinum),* and rainy season legumes, mainly soybean *(Glycine max),* mung bean *{Vigna radiata),* black gram *(Vigna mungo),* cowpea *(Vigna unguiculata),* and pigeonpea *(Cajanus cajan).* The grain legumes (lentil, khesari, chickpea, pigeonpea, black gram, and mung bean) are traditionally an integral part of the daily diet taken as *dhal* (soup) with *roti* (wheat bread) or *bhat* (boiled rice). In recent years, the importance of legumes has been increasingly recognized for enriching soil fertility through

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their ability to symbiotically fix atmospheric nitrogen (N) and tolerate drought hazards.

Rice-grain legumes cropping systems are long-standing traditional cropping patterns in Nepal. Wheat cultivation after rice is, however, a comparatively recent introduction (35-40 years). Introduction of wheat after rice has pushed grain legumes into less fertile and rainfed marginal lands because (i) wheat responds better to high fertility management, (ii) the Government's priority is to increase rice-wheat production, (iii) the profitability is probably better, and (iv) legumes have the ability to produce relatively better than other crops on marginal lands. However, there are increasing concerns that continuous rice-wheat cropping has caused mining of soil nutrients and general deterioration of soil health. Use of fertilizers is being promoted for raising the rice-wheat productivity and for maintaining soil fertility. However, the high cost of fertilizers, their unavailability at the right time, and limited purchasing power of farmers have limited extensive use of fertilizers in Nepal. Besides, the growing global concern of their environmental hazards has caused donors to reduce or stop fertilizer aid. On the other hand, there is evidence (Fujisaka et al. 1994) that even the use of recommended doses of fertilizers cannot sustain increased rice-wheat yields in the long run. As a result, yields of rice (2 t ha^{-1}) and wheat (1.4 t ha"^{1}) have stagnated over recent years. If the trend of stagnation or decline in rice-wheat production continues, the sustainability of rice-wheat cropping systems (RWCS) and food security in the country would be highly jeopardized.

Nitrogen is the most yield limiting plant nutrient universally deficient in Nepalese soils. Results of fertilizer trials and demonstrations over years and locations in Nepal have shown a high rice-wheat response to N application at levels of 100-150 kg ha^{-1} (Joshy and Deo 1976; Pandey 1991; Tripathi and Pandey 1996). Therefore, input of N into soil is essential to increase productivity. However, an abundant supply of N through mineral fertilizer alone has not been possible for the reasons indicated earlier.

Under such conditions, legumes offer an alternative non-cash source of N. Inclusion of legumes in the rice-wheat systems for production of grain, green manure or forage could play an important role in increasing crop productivity and restoring soil fertility through biological nitrogen fixation (BNF).

It has been well established that legumes derive a major portion of their N requirement through BNF. Under farm conditions in Nepal, it is estimated that legumes derive 70-90% of their total N requirement from this process (Table 1). Thus, legumes deplete less N from soil reserves than the cereals. Additionally, the plant residues (nodulated roots and above-ground biomass) if left after the crop harvest provide organic N and enrich soil with organic matter. Therefore, it is believed that crops following legumes are additionally benefited. However, the magnitude of their residual effect on enhancing soil fertility and crop productivity has not yet been systematically and thoroughly studied in Nepal. Recognizing this, the research project

"Management of legumes N_2 fixation for rainfed cereal production" has been operational at the Nepal Agricultural Research Council (NARC), Khumaltar, Nepal in collaboration with the Australian Centre for International Agricultural Research (ACIAR), Australia since 1993. It is expected that results from this project would answer some of the above questions and identify the future researchable issues to fill in the information gap (Rupela et al. 1997).

Table 1: Percent of nitrogen derived from atmosphere (%Ndfa) in different legumes under farm conditions in Nepal.

Legume species	No. of samples measured	%Ndfa Mean	%Ndfa Range
Lentil	10	86	83-89
Khesari	10	86	81-90
Faba bean	8	88	68-91
Soybean	10	72	56-100

Source: S. Bhattarai, NARC (unpublished).

PRESENT STATUS OF LEGUMES IN RICE AND WHEAT CROPPING SYSTEMS IN NEPAL

Major Legumes in Rice-Wheat Systems

Cropping patterns within the rice-based farming systems vary according to water availability and climatic and cultural differences. The cropping patterns in Nepal including major legumes with rice and in rice-wheat system are:

- Rice-lentil/khesari/chickpea-fallow
- Rice-lentil/khesari-early rice
- Rice-wheat-Sesbania/mung bean/cowpea (green manure)
- Rice + pigeonpea (on bunds)
- Rice + soybean (on bunds)

Besides, many minor legumes such as pea *(Pisum sativum)* and faba bean *(Vicia faba)* are grown as sole crops after rice or mixed with wheat. Among the legumes, lentil, khesari, and chickpea cover 70% of the total area of legumes grown in RWCS.

Trends in Area, Distribution, and Yield of Rice and Wheat

The area of rice cultivation did not expand significantly between 1975 and 1992, while that of wheat increased substantially (53%) from 0.37 million ha in 1975 to 0.57 million ha in 1992 (Fig. 1). The area of wheat in rice-wheat sequence was estimated at 0.43 million ha, i.e., 75% of wheat area in 1992.

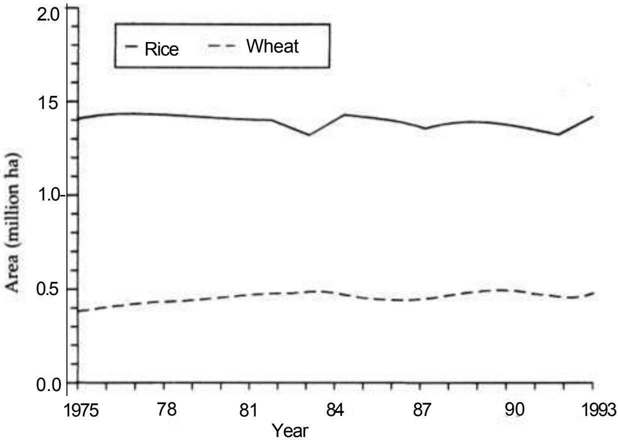

Figure 1: Trends in area of rice and wheat in Nepal during 1975-93.

The average yield trends for rice and wheat over nearly two decades have sluggishly increased or stagnated (Fig. 2). The national average yield for rice in 1975 was 2.01 t ha^{-1} which increased only to 2.28 t ha^{-1} in 1992. Similarly the national average yield for wheat over the same period increased from 1.13 t ha^{-1} to 1.36 t ha^{-1}

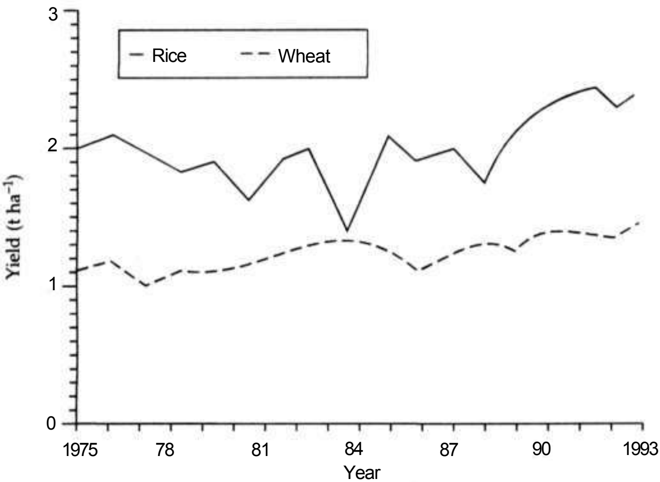

Figure 2: Trends in yield of rice and wheat in Nepal during 1975-93.

Trends in Area of Major Winter Grain Legumes

The area of lentil cultivation has increased significantly, particularly from 1990, due to its export demand. On the contrary, area of khesari and chickpea has substantially declined (Fig. 3). The decline in khesari area is mainly due to prohibition of its cultivation because of its potential role in causing lathyrism due to the presence of a neurotoxic compound. The decline in chickpea area has been attributed mainly to severity of Botrytis gray mold and wilt complex and high infestation of *Helicoverpa* pod borer. However, the total area of winter grain legumes has shown an increasing trend in recent years.

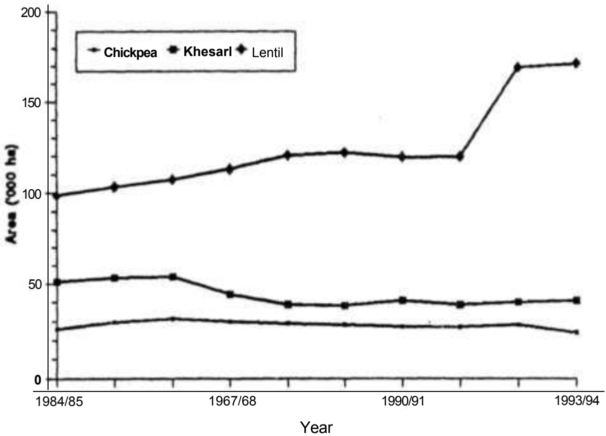

Figure 3: Trends in area of winter grain legumes in Nepal during 1984/85 to 1993/94.

Trends in Yield of Winter Grain Legumes

Whilst the trend in yield of lentil shows a marginal increase, those of khesari and chickpea are mainly static or declining (Fig. 4). Among these three grain legumes, lentil has maintained comparatively higher yield level followed by chickpea and khesari. However, the national yields of all the three grain legumes are low (<0.7 t ha^{-1}).

Spatial Distribution of Lentil and Chickpea Area in Nepal

Cultivation of lentil and chickpea in Nepal extends from the Terai to the mid-hill regions of the country (Figs. 5 and 6). The intensity of their cultivation, however, is mostly concentrated in the Terai districts where rice and wheat are also intensively cultivated.

Besides lentil and chickpea, other legumes such as pigeonpea, black gram, and mung bean are grown in rice-wheat systems. Pigeonpea is planted in

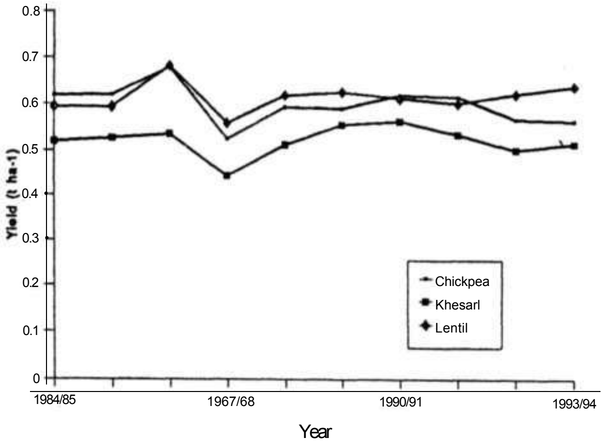

Figure 4: Trends in yield of winter grain legumes in Nepal during 1984/85 to 1993/94.

June on rice bunds and harvested in April. This practice, in addition to optimizing use of land area regulates water and nutrient recycling through the deep root system of pigeonpea and, therefore, may help in sustaining rice-wheat systems. Mung bean, cowpea, and *Sesbania* are grown as catch crops between rice and wheat crops in irrigated conditions for grain and green manuring purposes. However, the statistics of their area and distribution pattern are not recorded and are thus unavailable.

PROSPECTS OF INCLUDING LEGUMES AND ENHANCING THEIR RESIDUAL EFFECTS IN RICE-WHEAT CROPPING SYSTEMS

Prospects of Including Grain Legumes in Rice-Wheat Cropping Systems

There is considerable scope of increasing the lentil area, particularly in late-planted rainfed rice fields, because such fields are less suitable for wheat cultivation due to moisture deficit. Lentil requires little input of fertilizer and irrigation. It performs well even under relay cropping in rice and gives good profit margins because of low investment cost and high market price. If the present trend of its high price incentive and demand for export continues, intensification of lentil cultivation may further increase in the future.

Residual Effects of Legumes on Soil Fertility

It has been reported that in the tropics, 60-90% of N fixed by legumes may

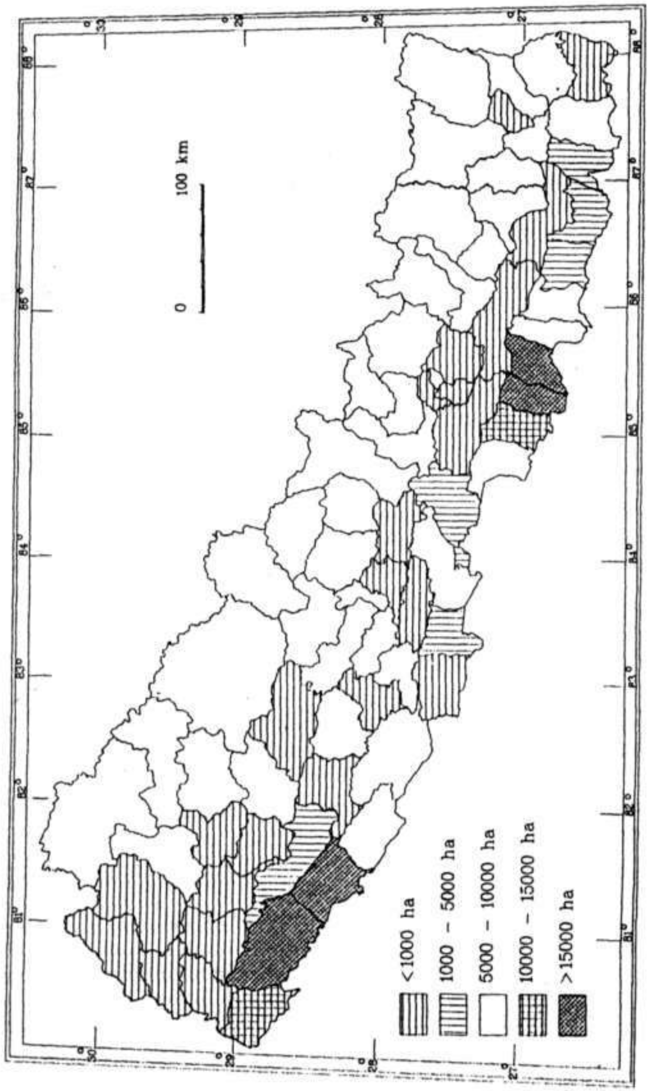

Figure 5: Spatial distribution of lentil area in Nepal during 1993.

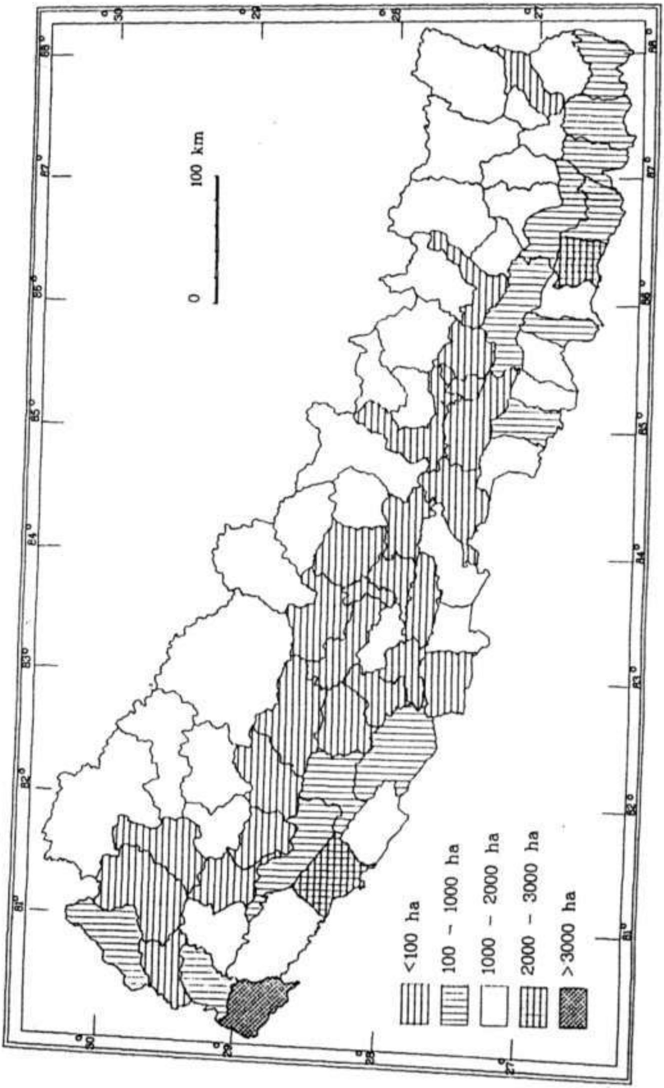

Figure 6: Spatial distribution of chickpea area in Nepal during 1993.

be removed with the harvest of seed or forage and the remaining 10-40% may be available to the subsequent crops through organic recycling (Henzell and Vallis 1975). Therefore, the residual effect of grain legumes (lentil, khesari, and chickpea) on enhancing the soil fertility and crop productivity in RWCS could be negligible when most of the above-ground plant parts are removed from the fields.

The uptake of N by legumes varies widely depending on the species of legumes, effectiveness of *legume-Rhizobium* symbiosis, and bio-physico-chemical properties of the soil. The amount of N fixed by legumes under various on-farm conditions in Nepal varies in the range 33-56 kg ha^{-1} with an average of 42 kg ha^{-1} for lentil and 24-80 kg ha^{-1} with an average of 55 kg ha^{-1} for chickpea (S.L. Maskey and S. Bhattarai, NARC, personal communication, 1996).

The magnitude of the residual effect on soil fertility and yield of a succeeding crop depends largely on the quantity and quality of plant residues returned into the soil. In Nepal, yield levels of grain legumes are low (500-1000 kg ha^{-1}) and most of the plant parts are removed from the field. As a result, the transfer of legume N to succeeding crops could be low.

Based on the preliminary statistics and taking a conservative value of about 40 kg ha^{-1} biologically fixed N, the main grain legumes [lentil, khesari, chickpea, pigeonpea, black gram, horse gram *(Macrotyloma uniflorum),* soybean, and others] grown in about 300,000 ha would however, add about 12,000 t free N yr^{-1} to the soil. Of this total amount, about 1,200 tons (by taking 10% minimum limit returnable to the subsequent crop as reported by Henzell and Vallis 1975) might be available to succeeding cereal crops. This, in monetary terms, amounts to about US$ 350,000 at the current price of fertilizer N from urea.

The other important advantages of legumes include the possible use of sub-surface soil moisture and plant nutrients through their deep root system. Similarly, legumes in rotation in rice-wheat systems would help disrupt the population build-up of insect pests (Gyawali 1989). Therefore, the importance of grain legumes in the sustainability of rice-wheat systems is immense.

Effect of Green Manure Legumes on Yield of Succeeding Rice Crop and Soil Fertility

There is extensive evidence for significant positive effects of legumes on succeeding rice crops when incorporated as green manure (Pandey 1983; Maskey and Bhattarai 1995). Experimental results have indicated that rice crops grown after legumes have yielded better than those grown after non-legumes (e.g., wheat) (S. Schulz, NARC, personal communication, 1995). The performance of white clover *(Trifolium repens)* was found outstanding for its biomass yield as well as for its residual effect on dry matter production of the succeeding rice crop (Table 2). The organic matter content of soil after legumes tended to increase more so than after wheat (Table 3).

Table 2: Effect of legumes on production of succeeding potato and rice crops in Kathmandu valley, Nepal during 1994/95.

Cropping pattern	Legume biomass in Feb[1] (kg DM ha^{-1})	Potato or wheat yield (t ha^{-1})	Legume biomass in June (kg DM ha^{-1})	Rice crop biomass (t DM ha^{-1})
Fallow-potato-rice		9.45	-	4.90
Pea-potato-rice	170	11.19	-	6.05
Lupin-potato-rice	364	10.05	-	5.78
Faba bean-potato-rice	266	11.98	-	4.72
Lupin-rice		-	875	5.98
Faba bean-rice		-	2086	7.29
Berseem-rice		-	3504	8.99
White clover-rice		-	13199	13.14
Wheat-rice		-	-	5.30
LSD (P = <0.05)		NS		2.05
CV (%)		29.6		20.3

[1]DM = dry matter.

Source: Potato Research Project, NARC (unpublished).

Table 3: Effect of legumes on succeeding rice yields and soil properties in Kathmandu valley, Nepal during 1994/95.

Previous crop	Legume foliage dry matter (t ha^{-1})	Yield of succeeding rice crop (t ha^{-1}): Grain at 12% moisture	Yield of succeeding rice crop (t ha^{-1}): Straw/ grain (dry matter)	Soil property after legume harvest: Organic matter (%)	Soil property after legume harvest: Total N (%)
Wheat (control)	-	5.20	9.43	3.0	0.159
Field pea	5.78	6.92	12.31	3.4	0.159
Milk vetch	7.15	7.51	13.57	3.5	0.162
Faba bean	6.43	7.47	12.94	3.5	0.160
Lentil	5.54	7.36	12.69	3.3	0.152
Khesari	6.58	7.11	12.77	3.3	0.152
Berseem	10.08	7.20	13.29	3.1	0.153
Sweet lupin	2.74	5.54	9.54	2.9	0.143
Bitter lupin	3.70	6.34	11.27	3.5	0.154
Pea	5.75	7.42	13.16	3.6	0.159
LSD (P = <0.01)		0.88	1.91	NS	NS
CV (%)	-	13.0	16.0	17	4

Source: S. Schulz (unpublished).

The green manure legume, dhaincha *(Sesbania cannabina)* grown in May-July after harvest of wheat could increase rice yield equivalent to an increase caused by about 50 kg fertilizer N ha^{-1} either incorporated alone or in combination with fertilizer N (Table 4). However, the residual accumulation of organic matter and N in the soil due to green manuring is not significant after rice harvest.

Table 4: Effect of dhaincha *(Sesbania cannabina)* green manuring on yield of succeeding rice crop at different levels of fertilizer N in a rice-wheat cropping pattern.

N applied ($kg\ ha^{-1}$)	Rice yield ($t\ ha^{-1}$)		Yield increase due to GM ($t\ ha^{-1}$)	Organic matter content after rice (%)	
	Fallow	GM[1]		Fallow	GM
0	3.34	3.92	0.58	1.59	1.60
25	3.71	4.33	0.63	1.40	1.60
50	4.05	4.47	0.43	1.40	1.61
75	4.28	4.64	0.36	1.40	1.61
100	4.50	4.98	0.47	1.80	1.71
Mean	3.98	4.47	0.49	1.52	1.63
LSD (P = <0.05)	0.35				

[1]GM = Green manure.

Source: Pandey (1983).

Maskey and Bhattarai (1995) studied the effect of green manure of legumes and non-legumes on the yield of a rice crop in rice-wheat cropping pattern (Table 5). The results show that rice yields following green manuring with legumes were higher than those with non legumes. Among the three legumes, *Sesbania cannabina* proved to be the best.

Table 5: Effect of different green manures on yields of succeeding rice crop in rice-wheat cropping pattern.

Treatment	Fresh biomass ($t\ ha^{-1}$)	Mean rice yield ($t\ ha^{-1}$)	Increase over control ($t\ ha^{-1}$)
Sesbania cannabina	23.6	4.898	1.837
S. rostrata	21.6	4.210	1.149
Mung bean	12.8	4.514	1.453
Azolla	10.0	3.767	0.706
Water hyacinth	10.0	3.144	0.083
Straw compost	10.0	3.652	0.591
Fertilizer[1]	-	4.227	1.166
Control	-	3.061	-

[1]100:40:30 kg NPK ha^{-1}

Source: Maskey and Bhattarai (1995).

Although the effect of green manuring on the following crop is large and significant, the practice has not been extensively adopted by farmers. This is probably because the crop grown for green manure does not directly yield any food or cash. Additionally, unavailability of seeds, irrigation water, and proper implements for incorporation of green manure are some of the constraints to its extensive use. Nevertheless, green manure transfers greater amount of N than the grain legumes for use by subsequent crops and therefore, has potential in sustaining RWCS from an N fertility point of view.

Comparative Productivity of Rice-Based Cropping Systems

A long-term rice-based cropping system experiment was initiated in the Kathmandu valley, with rice in rotation with legume (lentil), cereal [wheat and barley *(Hordeum vulgare)],* tuber [potato *(Solarium tuberosum)],* and oilseed [mustard (*Brassica* sp.)] crops. The results of the first three years of this ongoing experiment show that the contribution of rice-lentil system to the yields of following rice crop (Table 6) as well as to the profitability (Table 7) is not significantly different (or is even least in some years) from rice-cereal and rice-oilseed systems. The rice-potato cropping system produced the maximum rice yield and the highest profit. This is the main reason that farmers around Kathmandu valley have mostly shifted from a rice-wheat system to a rice-potato system. Under these conditions, replacing potato with legumes such as lentil cannot be advocated. Economic viability of the legumes in the cropping system is, however, very important for the sustainability of the system.

Table 6: Comparative productivity (t ha^{-1}) of rice-based cropping systems in Kathmandu valley, Nepal during 1992-95.

	1992/93		1993/94		1994/95		Mean	
Cropping pattern	Rice	Winter crops	Rice	Winter crops	Rice	Winter crops	Rice	Winter crops
Rice-wheat	4.37	2.66	5.21	3.01	3.13	2.56	4.23	2.74
Rice-lentil	4.41	0.37	5.32	0.63	3.66	0.59	4.46	0.53
Rice-potato	4.22	15.28	5.80	16.57	4.07	10.82	4.69	14.22
Rice-barley	4.31	2.42	4.99	2.49	3.57	2.67	3.99	2.52
Rice-mustard	4.49	0.41	4.92	0.58	3.66	0.47	4.35	0.49
LSD (P = 0.05)	NS	1.54	0.42	0.63	NS	1.09		
CV (%)	11.0	23.6	15.1	8.8	20.9	13.8		

Source: N.K. Rajbhandari, NARC (unpublished).

Table 7: Comparative annual net profit (Rs. ha^{-1}*)* of rice-based cropping systems in Kathmandu valley, Nepal during 1992-95.

Cropping pattern	1992/93	1993/94	1994/95	Mean
Rice-wheat	25524	38483	19210	27739
Rice-lentil	16696	31136	19008	22280
Rice-potato	62771	84609	47755	65045
Rice-barley	21258	30574	21747	24526
Rice-mustard	20371	28861	17576	22269

Source: N.K. Rajbhandari, NARC (unpublished).

Effects of *Rhizobium* Inoculum on Dry Matter Yields

Rhizobium inoculation can increase yields of soybean, black gram, and lentil by 10-65% in Nepal (Maskey and Bhattarai 1995). A number of efficient local as well as exotic N_2-fixing rhizobia were identified which could increase yields by as much as 70%. These results show that there is an ample potentiality to increase the productivity of legumes through BNF technology. Nevertheless, there are also a number of constraints to its extensive use. Some of the limiting factors for its extensive use are soil factors such as soil acidity, low phosphorus, low organic matter, and micronutrient (boron and molybdenum) deficiencies and socioeconomic factors such as lack of production, and proper transportation, storage, and distribution.

RESEARCH NEEDS

There is an increasing trend of inclusion of grain legumes in the cropping systems in Nepal because of their increasing market price. Hence, farmers will probably be more interested to put more area under pulse crops in the coming years. Besides, the declining rice-wheat system yields and profitability coupled with high cost of fertilizers may further force farmers to opt for low input based alternative cropping systems in rotation with rice-wheat. Legumes fit the best in this context. The major research thrust should be focused on:

1. Quantification of residual effects of commonly grown legumes for seed/grain, green manure, forage, pasture, and shade on the enhancement of soil fertility and yields of succeeding crops.
2. Identification of major soils and environment, agronomic, and genetic factors that restrict N_2 fixation and biomass production.
3. Evaluation of crop and soil management practices for increasing legume N_2 fixation.

CONCLUSION

On the basis of the foregoing discussion, the following inferences could be drawn.

- Grain legumes are still extensively grown in the rice-wheat cropping systems in Nepal, particularly in the Terai region. However, their yields are very low (<0.7 t ha^{-1}), stagnant, or have declined over the years.
- There is a large scope for inclusion of legumes (grain, green manure, and forage) in rice-wheat cropping systems in Nepal, particularly in the Terai region.
- The winter legumes fix 20-90 kg N ha^{-1} yr^{-1} and derive about 70-90% of their total N requirement through BNF under farm conditions in Nepal.
- There are many documented examples that show incorporation of green manure legumes into the soil contributes substantially (40-50 kg N ha^{-1}) to the succeeding rice crop. However, the information regarding

the beneficial residual effects of grain legumes on enhancing soil fertility and crop productivity is scanty and inconclusive.

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10

Overview and Prospects for Enhancing Residual Benefits of Legumes in Rice and Wheat Cropping Systems in Pakistan

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ABSTRACT

Rice and wheat are the most important staple foods in Pakistan. Both the crops are sequentially grown on an estimated area of 1.6 million ha. The double rice-wheat cropping system (RWCS) is highly exhaustive in nature and its continuous practice has resulted in low inherent soil fertility along with widespread deficiencies of macro and micronutrients. The current yield level of the system is below 5 t ha^{-1}, compared to a potential of 13 t ha^{-1}. Inclusion of legumes, however, can play a vital role in improving soil health and sustaining the productivity of RWCS.

In Punjab, intercropping of chickpea with wheat was once a common practice, but this has now disappeared due to ascochyta blight epidemics affecting chickpea. It can again become important if early-maturing and disease-resistant varieties of chickpea are provided to the farmers. Lentil is another potential grain legume which can be intercropped with wheat. In some areas of Sind and Baluchistan, rice-khesari is preferred over the rice-wheat rotation. Khesari can also be relay cropped with rice in Sind province. Pakistan is fortunate enough to have a 2-2.5 months fallow period between wheat harvest and rice transplanting. This period can effectively be utilized by fitting short-duration, dual purpose legumes such as mung bean or black gram in the RWCS. The practice will not only enhance soil fertility but also provide an additional source of farm income. Moreover, green manure legumes such as *Sesbania,* sunn hemp, and guar can be used to economize on the fertilizer nitrogen requirement of rice and increase paddy yield. A major constraint to non-adoption of green manure crops lies with its high cost of cultivation.

The prospects of using legumes in RWCS in Pakistan are bright subject to development of high-yielding, early-maturing, disease-resistant varieties of both cereals and legumes. There is also scope for improved plant protection measures

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to boost productivity of RWCS. There is a need to strengthen and stimulate the research base for achieving these goals. Characterization of different agroecological zones in which RWCS is predominantly practiced is important. Identification of green manure legumes (both pre-rice and post-rice) with high biological nitrogen fixation capacity along with the development of appropriate production technologies is being increasingly realized as a priority. Similarly, understanding nitrogen dynamics, residue conservation, and residual effects of phosphrous is also important. Furthermore, development of specific implements and techniques for intercropping systems is also desired.

INTRODUCTION

Pakistan is situated in the monsoonal subtropics between 24-37° N and 60-75° E. Out of a total geographical area of 79.6 million ha, only 21.4 million ha are being cultivated. About 80% of the cultivated area is irrigated while the remaining is rainfed (Government of Pakistan 1995a). The groundwater level in irrigated areas is generally high causing serious salinity and alkalinity problems. The temperature varies from 27°C to 45°C in May/ July and from 5°C to 20°C in December/January. The cultivated plains of Pakistan consist of alluvial soils which vary from clayey to sandy soils. Clay loams and sandy loams are more common. In the plains, wheat *(Triticum aestivum),* rice *(Oryza sativa),* cotton (*Gossypium* sp.), and sugarcane *(Saccharum officinarum)* are the major crops. Food grain crops occupy 11.9 million ha of the cultivated area. Wheat occupies 63% followed by rice which occupies 19% of the area under food grains.

In Sind and Punjab provinces, rice and wheat are grown sequentially as irrigated crops. The wheat season is during November/December to April/ May while rice is grown during July to November with seedling nurseries established in late April to May/June (Woodhead et al. 1993). The time of various field operations such as crop establishment and harvest shows some progression along the Indus Valley sequence: lower Sind-upper Sind-Punjab. The nursery may be sown in April in lower Sind, mid-May in upper Sind, and early June in Punjab. Rice transplanting proceeds through June and is essentially completed by the end of July. Rice harvest depends not only on seeding date but also on cultivars; it may extend from early October to late November (Byerlee et al. 1984; Bhatti 1987; Aslam et al. 1989). The type of cultivar generally differs between the Sind and Punjab rice-wheat sequences; high-yielding, fertilizer-responsive, semi-dwarf, non-aromatic rice varieties are mostly grown in Sind whereas the high-value aromatic (Basmati) cultivars feature in nearly all rice-wheat cropping systems (RWCS) in Punjab (Bhatti et al. 1984; Byerlee et al. 1984; Sharif et al. 1989). Grain yields in these sequences in recent years have been about 2.3 t ha^{-1} of paddy and 1.6 t ha^{-1} of wheat.

The RWCS is extensively practiced in Punjab (0.85 million ha) and Sind (0.56 million ha) provinces of Pakistan (Table 1). It is also seen in North-West Frontier Province (NWFP) and Baluchistan. Wheat yield is less (1.6 t ha"^{1}) when it is grown after rice than when it is grown in non-puddled soil

Table 1: Area ('000 ha) of rice, wheat, and major legumes under rice-wheat cropping systems in Pakistan, 1993-94[1].

Province / District	Rice	Wheat	Chickpea	Lentil	Mung bean	Black gram	Khesari
Punjab							
Gujrat	36.0	52.2	0.2	1.0	2.1	6.9	-
Sialkot	157.4	152.2	0.3	0.9	NA	16.5	-
Gujranwala	203.6	189.3	0.6	0.9	NA	0.1	-
Narowal	65.5	56.7	0.4	5.8	0.1	12.2	-
Mandi Bahauddin	49.4	100.8	0.8	2.2	0.1	0.2	-
Hafizabad	85.4	113.7	1.4	0.5	NA	NA	-
Sheikhupura	207.6	252.9	1.3	1.3	0.1	0.1	-
Kasur	47.3	163.5	0.8	0.6	1.2	0.4	-
Sind							
Jacobadad	137.6	44.9	28.3	0.5	-	-	29.4
Shikarpur	100.6	27.1	23.0	-	NA	NA	29.5
Larkana	209.3	58.1	7.9	2.0	-	-	21.2
Dadu	56.7	71.4	3.8	0.1	0.1	NA	10.5
Thatta	60.1	7.5	0.4	1.4	0.1	0.3	0.8
NWFP							
Dir	15.9	17.3	-	0.2	0.4	1.4	-
Swat	8.4	16.9	-	1.7	0.1	-	-
Malakand	6.9	*95*	-	NA	0.1	NA	-
D.I. Khan	5.4	28.6	25.4	NA	1.0	0.2	-
Kurram Agency	5.7	7.8	-	-	3.0	0.3	-
Bajaur Agency	4.5	10.4	-	4.0	0.1	NA	-
Baluchistan							
Nasirabad	48.0	37.5	7.4	-	-	-	-
Jafferabad	68.1	75.8	10.1	-	NA	NA	-
Total	1579.4	1193.8	112.1	23.1	8.5	38.6	91.4

[1] NWFP = North-West Frontier Province; - = non-existent; NA = negligible area.

Source: Government of Pakistan (1995b).

(2.1 t ha^{-1}) after other crops such as maize *(Zea mays),* sugarcane, and cotton. Similarly, rice yield in this cropping system is below the potential yield of about 6.0 t ha^{-1}. Crop yields in the sequence are constrained by many factors but low soil nitrogen (N) is the most significant one contributing to the yield gap. The soils in rice areas are low in native N fertility and at the same time fertilizer N-use efficiency is generally poor (30% compared to 40-50% under upland conditions), and so the responses to N fertilizers are particularly large. There is a net negative balance of major nutrients even with the application of the recommended dose of 120 kg N ha^{-1} and 26.2 kg phosphorus (P) ha*[1] (Zia et al. 1992). Singh (1988) reported that in Pakistan wheat after rice responded up to 75 kg N ha^{-1} and showed marginal response to 21.9 kg P ha"[1]. Unless adequate amounts of the nutrients are supplied, it will be difficult to sustain the high yield potential of RWCS on a long-term basis.

Rice and wheat are indeed important components of Pakistan's food requirement. Over the past 25 years, the country has witnessed tremendous progress in wheat and rice production. The average yield of rice has increased from 1.3 t ha^{-1} to 2.3 t ha^{-1} and that of wheat from 0.8 t ha^{-1} to 1.7 t ha^{-1} during the same period. This has been achieved mainly through the use of improved varieties combined with better crop and soil management practices. However, the yields of these crops are now not increasing with the same pace as in earlier years (Mann and Garrity 1994). The situation is quite serious in the traditional rice belt where yield of following wheat crop is very low compared to the adjacent non-rice area (Byerlee et al. 1984). The major concern is how the declining trend in the productivity of RWCS could be averted. It is now realized that the continuous use of RWCS has resulted in deficiencies of important nutrients such as N, P, and boron (B) (Zia et al. 1993).

Adequate and balanced nutrient supplies are essential factors in realizing the full potential of high-yielding varieties of rice and wheat. However, high prices, low efficiency, and unavailability of chemical fertilizers impose serious limitations to their application. This situation calls for devising a sound strategy to help improve soil fertility and sustain crop productivity.

Long-term sustainability of cropping systems must rely, as far as possible, on the use and effective management of natural resources. Legumes offer economically attractive and ecologically sound means of reducing external inputs and improving the quality of soil health and cereal crop yields. Several green manure legumes are commonly used in the RWCS (Table 2). Biomass

Table 2: Some common green manure legumes suitable for rice-wheat cropping systems and their potential nitrogen contributions.

Common name	Botanical name	Green biomass (t ha^{-1})	N accumulation (kg ha^{-1})
Dhaincha	*Sesbania aculeata*	20	86
Sunn hemp	*Crotalaria juncea*	21	91
Guar	*Cyamopsis tetragonoloba*	20	68
Berseem	*Trifolium alexandrinum*	16	67
Cowpea	*Vigna unguiculata*	15	74
Mung bean	*Vigna radiata*	8	42
Black gram	*Vigna mungo*	11	44
Senji	*Melilotus alba*	28	163
Lentil	*Lens culinaris*	5	36
Pea	*Pisum sativum*	13	58
Moth bean	*Vigna aconitifolia*	9	31

Source: Modified from Tarar (1960).

production and N accumulation in different species vary depending upon duration, management practices, and climate. Grain legumes are incorporated in the soil after pod harvest, thereby contributing some N to the succeeding cereal crop. Such dual purpose legumes not only increase farm income but also improve soil physical properties. The present paper discusses the role of legumes in improving and sustaining the productivity of RWCS in Pakistan.

PRESENT STATUS OF LEGUMES IN RICE-WHEAT CROPPING SYSTEMS

Grain Legumes

The major grain legumes grown in Pakistan are chickpea *(Cicer arietinum),* lentil *(Lens culinaris),* khesari *(Lathyrus sativus)* (as a dual purpose legume), mung bean *(Vigna radiata),* and black gram *(Vigna mungo).* Chickpea, lentil, and khesari are grown after rice on residual moisture in the post-rainy season. Chickpea is predominantly cultivated in Punjab and Sind whereas khesari is exclusively grown in Sind and Baluchistan. Mung bean and black gram are important rainy season or summer grain legumes. These are mainly grown on poor to marginally fertile soils under rainfed conditions but are also cultivated, and have good potential to grow in rice-based cropping systems. The area and production of legumes in RWCS and in other cropping systems in Pakistan are presented in Table 3.

Table 3: Area ('000 ha) and production ('000 t) of rice, wheat, and major legumes in cropping systems in Pakistan during 1993-94.

	All cropping systems		RWCS[1]	
Crop	Area	Production	Area	Production
Rice	2187	3995	1609	3095
Wheat	8034	15213	1494	3196
Chickpea	1045	411	112	77
Khesari	138	74	91	40
Lentil	52	28	23	11
Mung bean	168	69	9	4
Black gram	65	29	39	14

[1] Rice-wheat cropping systems.

Source: Government of Pakistan (1995a).

Rice cultivation in Pakistan is entirely based on irrigation and this leaves sufficient residual moisture for succeeding legumes such as chickpea and lentil. Chickpea and khesari are important grain legumes which fit well into RWCS in Sind and Baluchistan provinces. The rice area in Punjab can also support the rice-chickpea system provided high-yielding, early-maturing, ascochyta blight-resistant varieties of chickpea, better agronomic management techniques, and pod borer control measures are available. Lentil is generally grown on a limited scale after rice in Punjab. In Narowal district, lentil is a very popular crop after rice, utilizing the residual moisture. Farmers sometimes get more profit from lentil than from wheat. One of the major production constraints is the high weed infestation in lentil fields. Lentil is a weak competitor with weeds, and as a result yields are drastically reduced. Non-availability of varieties having resistance to rust and orange cotyledons are the other limiting factors in lentil cultivation. In some parts of Gujranwala and in Sheikhupura districts, rice-pea *(Pisum sativum)*-okra *(Hibiscus* *esculentus)*/wheat cropping pattern is also practiced. In such areas, farmers grow early-maturing non-aromatic rice from June to September and pea from September end to early December. Wheat is then planted by mid-December.

High-yielding and disease-resistant varieties of mung bean are also grown but presently only a small area is under cultivation in RWCS. Non-availability of short-duration, photo-insensitive, and heat-tolerant mung bean cultivars to fit in the system poses problems. Non-availability of irrigation water is also a common constraint since the mung bean crop normally requires at least two irrigations for good yields. Mung bean normally has less disease and insect problems when sown prior to rice. Different cropping patterns were tested at the Rice Research Institute (RRI) in Kala Shah Kaku and compared with the standard cropping pattern of rice-wheat for four years (Table 4). *Rice-Brassica juncea-mung* bean emerged as the most profitable pattern, followed by rice-berseem *(Trifolium alexandrinum)* system over the traditional RWCS. A survey to determine the economic potential of mung bean and sunflower *(Helianthus annuus)* in the districts of Daska, Sheikhupura, and Hafizabad indicated that short-duration (55-60 days) mung bean varieties can be grown after wheat and before rice (Amir 1986).

Table 4: Comparison of different rice-based cropping systems for economic return.

	Increase over RWCS[1] (%)			
Cropping system[2]	1981/82	1982/83	1983/84	1984/85
Rice-berseem	29	19	35	24
Rice-lentil-dhaincha	-[3]		16	
Rice-Brassica-mung bean[4]	33	78	66	43
Rice-Brassica-sunflower	18		17	

[1]Increase over rice-wheat cropping systems (RWCS) calculated on the base price and income generated during the year; the net income of RWCS was Rs 1817 in 1981/82, Rs 2220 in 1982/83, Rs 6498 in 1983/84, and Rs 6088 in 1984/85.

[2]Standard management practices were adopted to grow the crops in a given rotation.

[3]Experiment damaged due to heavy flooding.

[4]*Brassica juncea,* locally known as *poorbi raya* was used.

Source: RRI (1982, 1983, 1984, 1985).

Black gram is another commonly cultivated grain legume in rice-based cropping system. This is grown particularly in areas where the water supply is scanty or it depends on rains. Black gram cultivation could not make much headway in RWCS due to lack of high-yielding, photoperiod-insensitive, and short-duration varieties.

Fodder Legumes

The important fodder legumes of RWCS in Pakistan include khesari, berseem, and cowpea *(Vigna unguiculata).* Khesari is grown exclusively in the provinces of Sind and Baluchistan as a winter legume to provide green fodder for livestock (60%) and dry grain both for animal and human consumption (40%). In terms of area sown, it ranks third among legume crops on an overall basis and second in RWCS (Table 3). On account of its high value as a winter green fodder, it is regarded more as a fodder crop rather than a food crop. Being extremely hardy and tolerant to drought, waterlogging, and salinity, and due to low cost of production, the small farmers in Sind favor the crop. Besides, it also enriches the soil to a greater extent due to its high nodulating potential (Thakur and Rai 1985).

Berseem is a common fodder legume grown after rice harvest both in Punjab and Sind. The estimated area under this legume is 0.82 million ha with total production of 2.54 million t. Experiments revealed that the rice-berseem rotation gives greater monetary gains than the standard RWCS (RRI1982,1983,1984,1985). It also helps improve the fertility of the soils. In Pakistan, berseem provides an excellent form of weed control in the subsequent rice and wheat crops (Byerlee et al. 1986).

Cowpea is another legume of rice-based cropping systems used mainly for fodder. It is traditionally grown as a mixed crop with sorghum *(Sorghum biclor),* millets, and maize in uplands. Insensitivity to photoperiod and resistance to seed damage caused by rain are the desirable traits for a cowpea variety to be sown as a pre-rice crop. The pre-rice crop of cowpea may mature during the onset of rains. The frequent wetting and drying of seeds coupled with high humidity affects seed quality. A variety tolerant to this field weathering is needed. Presently no variety having such desirable characteristics is available for adoption by growers. Non-availability of a suitable dual purpose (grain and fodder) variety is another hurdle in introducing cowpea into RWCS.

Green Manure Legumes

Although the RWCS offers greater stability in production, the productivity of this cropping sequence has been reported to decline in recent years (Mann and Garrity 1994). Cereal crops impoverish the soil of its nutrient reserves unless due care is taken to apply adequate and balanced nutrients. Inclusion of a green manure legume in the rotation can reduce the dependence on chemical fertilizer for the rice crop, and improve the physical characteristics of the soil. A fallow period of 50-70 days is available after wheat harvest and thus allows a suitable fast-growing legume to be fitted into the system. Immediately after the harvest of wheat, a green manure crop can be sown and plowed in during land preparation for transplanting rice. Generally wheat is planted immediately after rice harvest giving a short turn-around period for land preparation to farmers. Thus, establishing a green manure crop before wheat does not seem possible.

Non-grain legumes such as *Sesbania* sp., sunn hemp *(Crotalaria juncea),* and guar *(Cyamopsis tetragonoloba).* are mostly used as green manure in the RWCS in Pakistan. *Sesbania aculeata* (dhaincha) is tolerant to flooding and is extensively used in rice areas to reclaim the saline soils (Gill 1966; Mann and Ashraf 1986). In an experiment, use of *Sesbania* as a green manure increased wheat yield in a problem soil at the level obtained in a normal soil (Muhammad 1957). Green biomass production and N accumulation may increase when *Sesbania* is planted at optimum moisture condition rather than sown in flooded condition (Table 5). *Sesbania,* when grown for a period of 8-9 weeks as a pre-rice green manure, significantly increased the yield of the following rice crop but had no residual effect on subsequent wheat crop. Green manure also improved N uptake in rice-crop from 30% to 72%.

Table 5: Effect of *Sesbania* green manure (GM) and mineral nitrogen (N) on the grain yield (t ha^{-1}) of rice and wheat[1].

N rate (kg ha^{-1})	No GM	GM sown in water[2]	GM sown at optimum moisture	GM sown at optimum moisture and decomposed[3]	Mean[4]
Rice					
0	1.34	1.76	1.94	2.26	1.82c
67	2.69	3.17	3.68	3.21	3.19b
135	2.82	3.84	4.39	4.11	3.79a
202	3.24	3.89	4.39	3.53	3.76a
Mean	2.52c	3.16b	3.60a	3.28ab	
Wheat					
0	1.25	0.98	1.22	1.05	1.13c
67	2.01	1.76	2.40	1.41	1.89b
135	2.85	2.79	2.63	2.63	2.72a
202	3.18	2.59	3.07	2.94	2.95a
Mean[5]	2.32 ns	2.03 ns	2.33 ns	2.01 ns	

[1]The experiment was conducted on a loamy soil with pH 7.8 and organic matter content 0.55%. Inorganic N fertilizer was applied in the form of urea.

[2]*Sesbania aculeata* was sown in wheat-stubbled field after flooding and was grown for 8-9 weeks. Rice transplanting was done 2 days after its incorporation.

[3]*Sesbania* was rotated and allowed to decompose for 21-22 days.

[4]Means were separated using DMRT at 5% level.

[5]ns = not significant.

Source: Bhatti et al. (1984).

Sunn hemp is tolerant of drought and water stress and may be used in rainfed systems. Inclusion of short-duration *Vigna* spp. in RWCS can give the dual benefits of providing grains for human consumption and straw as green manure for rice. Similarly, guar is also a dual purpose legume cultivated both as fodder and as green manure. *Sesbania rostrata,* a stem-nodulating exotic species has high N-fixing potential and can offer greater prospects as a green manure crop. Over the past few decades, the practice of using these crops as green manures has declined probably due to high cost of labor, land preparation, shortage of irrigation water, and difficulties associated with fitting these into the prevailing cropping system with high cropping intensity and without displacing some remunerative crop (Garrity and Flinn 1988). Research work targeted at identifying high N-fixing legumes and reducing their cost of production is needed.

The primary value of green manure legumes as a source of N is realized when the green manure decomposes and its organic N is mineralized. Thus, if a green manure decomposes rapidly and releases its N quickly, it is an excellent source of N for the first crop (Bouldin 1988). In most cases, green manure-N exceeds 120 kg ha^{-1}. These levels are more than sufficient for the following Basmati rice crop, leading to occasional residual effects on the following wheat crop. Hussain et al. (1988) studied the integrated use of organic and inorganic N fertilizer and observed that green manure combined with prilled urea initially applied to rice had a significant effect on wheat yield. It appears, therefore, that the residual effects of green manure legumes are largely related to the green manure-N level and quantity of N recovered by the first crop.

PROSPECTS FOR INCLUDING LEGUMES AND ENHANCING THEIR RESIDUAL EFFECTS

Poor yields of rice and wheat are the prime concerns associated with the predominant RWCS in Pakistan. Low soil fertility, particularly with respect to soil N and organic matter, is the key factor, responsible for the decline in productivity of the cereal-cereal system (Zia et al. 1992). Application of inorganic N fertilizer, is, however, a major expense for small-scale farmers. Most of the time, the RWCS does not meet the dietary requirement of protein. Thus the inclusion of legumes in the cropping system is logical and imperative for agricultural sustainability. Legume crops fix atmospheric N in their root/stem nodules, add substantial amounts of underground biomass and litter, improve the physical condition of the soil, and perform better than the cereals under moisture and nutrient stresses (Singh 1984; Qixiao and Tiaren 1988; Rinaundo et al. 1988). Various legume-based management options that could offer some promise to the farmers in RWCS in Pakistan include crop rotations, green manuring, and intercropping. A brief account of these options is presented.

Crop Rotations

Crop rotation is perhaps the most common farming practice used to exploit N contribution of legumes. Legumes are universally regarded as beneficial to crop rotations on the general assumption that they improve soil fertility mainly by adding N. Cereal crops grown in rotation often yield more than when grown in monoculture (Curl 1963; Arnon 1972; Mannering and Griffin 1981). Crop rotations usually increase soil organic matter content, when compared with monoculture (Odell et al. 1984; Dick et al. 1986a, 1986b; Johnston 1986; Hargrove and Frye 1987; Havlin et al. 1990). Rotating legumes with cereals, once common in cropping systems in Pakistan, has been eliminated or simplified due to production intensification, government commodity programs, and short-term economic decisions. Cultivation of legume crops also declined due to high infestation of diseases, insects, and weeds in these crops. The blight fungus *(Ascochyta rabiei)* and pod borer *(Helicoverpa armigera)* are major pests of chickpea, an important food legume of the rice-wheat sequence. Another possible reason for the reduced use of legumes in the cropping system is the introduction of fertilizer and chemicals for pest and disease control. These problems can be tackled with the development of suitable legume varieties and reduction in cost of production by establishing such practices as zero tillage.

Chickpea and khesari fit well into the RWCS of Sind and Baluchistan provinces, replacing the staple cereal wheat. But in Punjab province, chickpea has disappeared from the system due to instances of complete failure of the crop caused by epidemics of ascochyta blight, a devastating foliar disease caused by *A. rabiei.* The cultivation of chickpea in the region can be restored by providing farmers with early-maturing, ascochyta blight-resistant varieties, and better production technologies such as stand establishment, and weed and pod borer control. Research work at the National Agricultural Research Centre, Islamabad, Pakistan is underway to develop high-yielding, short-duration, blight-resistant, and high input-responsive chickpea varieties to suit rice-based cropping systems. Moreover, the cultivation cost of chickpea is lower than that of wheat with a produce price thrice that of wheat; so farmers would definitely be interested in receiving more income from their land. In crop rotation experiments conducted at the RRI, Dokri, Pakistan, Bhatti (1987) observed that rice-chickpea rotation gave maximum monetary return followed by rice-lentil and rice-khesari sequences.

Similarly in Punjab, planting of lentil after rice can be augmented with testing of short-duration varieties for planting after Basmati rice. Early-maturing cultivars of lentil may be more profitable than wheat planted in December. This emphasizes the need of testing lentil breeding material for short duration to follow rice in Punjab.

In Sind and Baluchistan, the rice-khesari rotation is sometimes preferred over the standard rice-wheat rotation. This legume has the ability to out-perform other winter crops, including chickpea, in many ways. After rice harvest, land becomes available only very late for planting of the succeeding crop. Khesari is tolerant to waterlogging conditions and so the seed can be broadcast into standing water of the final irrigation of rice fields. Unlike in Sind, in Punjab there is not much scope for khesari in rice areas because of farmers' preference for chickpea over khesari.

In RWCS of the Punjab province, there exists scope to increase the cropping intensity by utilizing the period of about two and half months after the harvest of wheat, from 1st week of May to the 2nd week of July (Fig. 1). For the system to work effectively there is a need to develop genotypes of mung bean and/or black gram with 60-70 days maturity so that the land may be vacated in time for the next rice crop. Mung bean cultivar NM 92, being less photosensitive and of short duration may offer promise in this regard. Similar

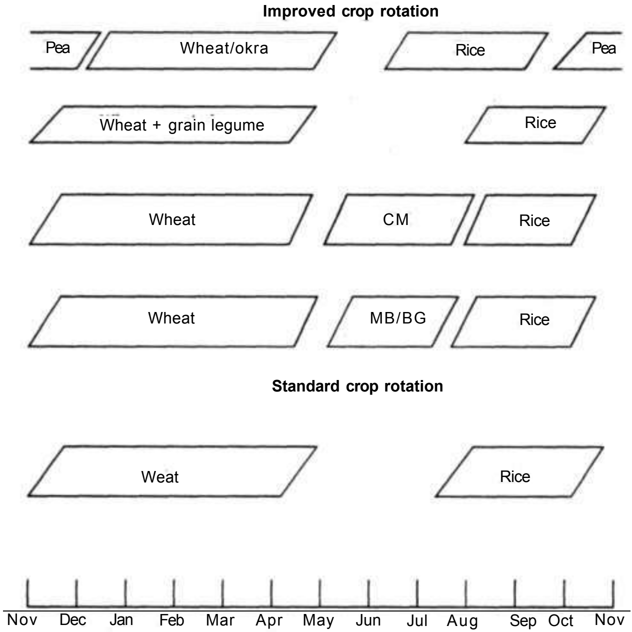

Figure 1: Improved rice-wheat cropping systems using legumes (GM = green manure; MB = mung bean; BG = black gram).

behavior has also been shown by a promising black gram line 9025. Rice-berseem-rice is also a popular crop rotation in some rice-growing areas. Berseem being a dual purpose legume has greater prospects in RWCS as its first 2-3 cuttings can be used as valuable green fodder for livestock and it can then be plowed in as a green manure for the next rice crop.

Green Manuring

Sesbania aculeatd can be successfully grown as a pre-rice green manure and incorporated into the soil during the puddling operation of rice transplanting in July. It can be either relay cropped with wheat in March or planted immediately after the wheat harvest. The farmers in Pakistan find it difficult to invest on a third crop (green manure) with no direct cash benefit. Thus, an effective stand establishment at low cost is essential for the economic viability of the system (Garrity and Flinn 1988). In a number of experiments, it was observed that *Sesbania* grew well and contributed substantial amount of N in no-tilled soil immediately after wheat harvest through broadcasting the seed in the standing water. The farmers simply need to invest in the seed for green manuring. *Sesbcmia rostrata,* a tropical legume with high N_2-fixing potential due to stem nodulation, has given very encouraging results. The legume produces more biomass and N in about 60 days than the indigenous varieties of *S. aculeata* (RRS, PARC 1995). In an experiment, three legumes were evaluated under different establishment techniques and it was found that *S. rostrata* established with zero tillage by broadcasting produced higher paddy yield as compared to relay cropping and line sowing (Table 6). *Sesbania aculeata* ranked second in increasing paddy yield.

Table 6: Effect of green manure legumes established by various methods on the grain yield of rice and wheat[1].

	Grain yield (t ha^{-1})	
Treatment	Rice	Wheat
Control	2.44	1.15
80-50 kg N-P ha^{-1}	3.51	2.81
Sesbania rostrata sown in wheat	3.72	3.10
S. *rostrata* sown after wheat in water	3.94	3.01
S. rostrata sown at optimum moisture	3.54	2.90
S. aculeata sown in wheat	3.59	3.05
S. *aculeata* sown after wheat in water	3.48	2.85
S. *aculeata* sown at optimum moisture	3.50	2.88
Crotalaria juncea sown in wheat	3.01	2.97
C. *juncea* sown after wheat in water	3.20	2.93
C. *juncea* sown at optimum moisture	3.32	2.83

[1]Basmati-385 was transplanted at 2-3 days after the green manure incorporation. Green manure crops were grown for 58 days and accumulated N from 35 kg ha^{-1} (C. *juncea)* to 74 kg ha^{-1} (S. *rostrata). A* uniform dose (40 kg N ha^{-1}) in the form of urea was applied to green manured plots at panicle intiation of rice, while the recommended dose of 100 kg N ha^{-1} and 50 kg P ha^{-1} was applied to all wheat plots.

Source: RRS, PARC (1995).

It is suggested that *S. rostrata* has bright prospects in replacing the traditional S. *aculeata* crop for sustaining the fertility of exhausted paddy soils. The cost of tillage and labor for seeding is negligible in this system. Hussain et al. (1995) found *S. rostrata* superior to *S. aculeata* and *Cyamopsis tetragonoloba* in terms of biomass production and N accumulation. *Crotalaria* is a good green manure crop for well-drained areas. Similarly, short-duration and high-yielding varieties of grain legumes of the genus *Vigna,* such as cowpea and mung bean, can be established in the 60-70 day fallow period. After the harvest of pods, crop residues are incorporated into the soil. Fodder legumes such as berseem and senji(*Melilotus alba)* may also grow well following rice. The final cutting of berseem can be buried in the soil to improve soil fertility. This practice could be practiced once in three years. The fitting of legumes in the RWCS is also important to break the cycles of insect pests and weeds. One-year rotation may not be so effective to generate visible effects on soil health or on the subsequent wheat crop. At least three cycles of fitting legumes in RWCS are essential to observe a significant response to crop yield or soil quality improvement (Tarar 1960; Gill 1966).

Intercropping and Relay Cropping

Food legumes are widely grown in rotation or interplanted with cereals either as crops for grains or as green manure. In canal irrigated areas of western Punjab, chickpea has been commonly interplanted with wheat. Recently, the chickpea area under pure stand and intercrop has substantially declined. Inclusion of legumes in the cropping system can increase the total N output but does not necessarily result in a positive soil N contribution (George et al. 1992). The quantity of N_2 fixed by the legume in an intercrop depends on the species, morphology, legume density, and crop management. The biological nitrogen fixation (BNF) varies with legume species in both monocultures and mixed cropping systems. Differences in the competitive abilities of the component crops for soil N can stimulate N_2 fixation in the intercrop (Peoples and Craswell 1992). The potential intercropping or relay cropping systems of RWCS in Pakistan using legumes are: (1) Wheat + lentil (intercropping); (2) Wheat + *Sesbania* green manure (relay cropping); (3) Rice + khesari (relay cropping).

Lentil can be successfully grown as a mixed crop with wheat and *Brassica* sp. The highest land equivalent ratio (1.25), gross benefit, net benefit, and benefit-cost ratio were obtained from 100% lentil and 33% wheat combination in Bangladesh (Zaman 1989). *Sesbania,* if planted in wheat in March with final irrigation and plowed in after wheat harvest, can substantially contribute to land productivity. Similarly, khesari seed can be broadcast in rice fields near maturity, thus serving as a good green manure for the forthcoming wheat crop. Berseem intercropped in September planted new sugarcane is also a potentially good combination. The first one or two cuttings could be taken as green fodder for the livestock and then plowed in as green manure for the standing component crop.

FUTURE RESEARCH NEEDS

The RWCS is very exhaustive in nature. Hence, research work on the following issues must be undertaken in the future, if the goals of improved productivity and sustainability of RWCS in Pakistan are to be achieved.

- Many factors, namely low soil organic matter content, low fertilizer application, creation of hard pan, no crop residue incorporation, and poor soil physical conditions contribute to declining soil fertility, but management of N remains crucial. Hence, the role of biologically fixed N in the system continues to justify considerable research on basic as well as applied aspects. Legume BNF may not be a panacea, but it is often the most feasible and economical N input for resource-poor farmers.
- The RWCS is being practiced in different agroecological zones such as upper Sind, lower Sind, and Kalar Tract of Punjab. There is a need to

categorize the edaphic and climatological conditions of each zone. Emphasis must also be given on conducting long-term studies on the sustainability of the cropping system as a whole rather than on an individual crop.

- So far, research on N dynamics has been primarily on the pre-rice legume system. There is a need to identify suitable post-rice legumes coupled with the development of early maturing, non-aromatic rice and ascertain legume effects on N contributions to the system.
- To increase farm income from the RWCS, fitting of fast-growing, short-duration, and dual purpose legumes is essential. Research needs to be focused on the development of production technology for legumes such as mung bean and cowpea. In Pakistan, chickpea is grown in diverse ecosystems each with its own production problems. Legume genotypes, especially of chickpea with early-maturity, responsiveness to high N inputs, and tolerance to salinity are more specifically required for rice-based farming.
- In view of N-deficient soils and inadequate application of fertilizer by the farmers to rice or wheat crop, mineral N fertilizer is likely to continue to be the main source of N for the sustained high yields of cereal crops. Priority should be given to research which integrates inorganic and organic sources of N aimed at increasing nutrient-use efficiency with minimum risks of excessive N accumulation and environmental pollution.
- Identification of suitable green manure legumes along with their low-cost production technology may be significant for their expanded adoption. *Sesbania rostrata,* having high N-fixing ability, could prove a good green manure in local climates. Detailed research on its biological and physiological aspects is required. There is a need to investigate socio-physical and technical constraints to non-adoption of green manures by the farmers.
- Legume N contribution to succeeding rice crop is directly linked with losses of nitrate N formed from mineralization of soil organic matter and legume N. The anaerobic-aerobic soil cycles, a typical feature of lowland rice-legume pattern can lead to higher N losses. Ways and means must be explored to minimize these losses in lowland rice-legume sequences.
- As two physically and physiologically different crops are planted in an intercropping system, a new set of equipment, tools, and techniques are required for seeding, interculture, and other farm operations. In Pakistan, research work needs to be undertaken to devise and modify appropriate machinery and tools for potentially important intercropping systems.

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11

Overview and Prospects for Enhancing Residual Benefits of Legumes in Rice and Wheat Cropping Systems in India

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ABSTRACT

Rice-wheat is the most widely adopted double cropping system in India covering an area of 10.5 million ha. As both rice and wheat crops are exhaustive feeders of plant nutrients, continuous cultivation of these two cereals in sequence has led to depletion of inherent soil fertility resulting in a serious threat to sustainability of this important cropping system. Inclusion of legumes in Rice-Wheat Cropping Systems (RWCS) has shown promise in augmenting the productivity of the system and maintaining soil fertility. Experiments under the All India Coordinated Agronomic Research Project of the Indian Council of Agricultural Research (ICAR) and other research programs have established the beneficial effect of growing legumes as catch crops, green manure, or fodder crops; the magnitude of benefit, however, depended on the agroecology of the area, availability of irrigation, and type of the legume crop grown. Depending on the soil and environmental stresses witnessed in rice or wheat crops, the RWCS can be diversified using legumes as substitute crops. Legumes introduced in the system leave a sizable residual effect, especially nitrogen for use by the succeeding crop. But this is not the only beneficial role of legumes. In a real sense, improvement in soil physical characteristics, mining of nutrients from deeper layers, and breaking of the cycle of pests and weeds are other important avenues which need detailed experimentation. Despite establishment of significance of legumes in RWCS, the low yield, high vulnerability to weather aberrations, and high sensitivity to pests and diseases limit their expansion in the rice-wheat growing areas. Therefore, in order to enhance the acceptability of legumes in RWCS, both legume breeders and resource management scientists have to work together for tailoring legume varieties to suit specified systems. The present article reviews various important aspects of inclusion of legumes in RWCS. Knowledge gaps and future research priorities have also been outlined.

The rice-wheat cropping system (RWCS) has a long history in India especially in the upstream sections of the Ganges Valley where the system was

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established well before independence. As early as 1872, in the Almora district of Uttar Pradesh, growing rice (*Oryza sativa)* sequentially with wheat *(Triticum aestivum)* or barley *(Hordeum vulgare)* was a common practice (Huke and Huke 1992).

In recent years, due to a massive shift in cropping pattern in Northern India owing to changes in the varietal scenario supported by area expansion under irrigation and increase in use of agro-chemicals, RWCS has assumed great significance in the country in view of its prolific growth in terms of area, production, and productivity. Uttar Pradesh, Punjab, Haryana, Bihar, and West Bengal are now the heartlands of this cropping system in India. The area under RWCS is estimated at 10.5 million ha (Pandey 1992).

Both rice and wheat are exhaustive feeders of nutrients. A system yielding 6.95 t ha^{-1} rice and 3.86 t ha^{-1} wheat may remove as much as 315 kg nitrogen (N) ha^{-1}, 28 kg phosphorus (P) ha^{-1} and 333 kg ha^{-1} potassium (K) apart from significant amounts of different secondary and micronutrients (Hegde and Dwivedi 1992a). Removal of N, P, and K in rice-wheat system at average productivity levels in different rice-wheat growing states indicates that nutrient removal is much higher than the average fertilizer consumption. Nutrient uptake data in rice-wheat system from long-term fertilizer experiments (LTFEs) indicate that there is a negative balance of N, P, and K even with recommended fertilizer use (Nambiar 1994). Unless the system is provided with adequate amounts of required nutrients, there will be a much greater drain on the native soil fertility and soil will not be able to sustain high productivity in future. A large number of experiments on complementary use of organic manure and chemical fertilizers conducted in different parts of the country indicate that neither chemical fertilizers alone nor the organic sources can achieve the production sustainability under this highly intensive cropping system. Even the so called balanced use of chemical fertilizers when practiced continuously over years is not able to sustain high productivity due to deterioration in soil physical properties and emergence of the deficiencies of one or more of secondary and micronutrients.

Under such situations, if legumes which are known to fix atmospheric N and enrich soil fertility are introduced in the system, productivity might be sustained over a period of time. Farmers have also realized the value of legumes as agents of restoring soil fertility. Hence they generally raise legume crops after the exhaustive crops of cereals in order to replenish soil fertility. The present article reviews the status and prospects of legumes in sustaining rice-wheat productivity and soil health.

PRESENT STATUS OF GRAIN LEGUMES IN RWCS

With the introduction of high-yielding varieties of rice and wheat and expansion of irrigation facilities during the Green Revolution, area under these two important cereals increased markedly. Both rice and wheat, being more productive and relatively less susceptible to different biotic and abiotic production constraints compared with legume crops, easily replaced the legumes and other less productive crops such as millets, wherever any kind of development of irrigation infrastructure or farmers' economic conditions took place. In 1960-61, the area under rice was 34.13 million ha and that under wheat was 12.97 million ha; in 1993-94, the area under rice expanded to 42.03 million ha and that under wheat to 24.91 million ha (FAI 1995). During the three decades, the area under pulses remained almost constant, and only a negligible increase of <1.0 million ha was recorded. Even this small increase in area of pulses was mainly ascribed to new marginal lands brought under cultivation or to the lands not fit for rice or wheat cultivation. These trends in area resulted in stagnant production of pulses, of about 12-13 million t, whereas the production of rice and wheat increased manifold. The area and production of pigeonpea *(Cajanus cajan)* decreased sharply in the states of Uttar Pradesh, Bihar, West Bengal, and Rajasthan although some increase in both area and production was noticed in Madhya Pradesh. In 1960-61, the area under pigeonpea was negligible in Punjab and Haryana; however, in 1993-94 it increased to 11 thousand ha in Punjab and 50 thousand ha in Haryana (Table 1). Chickpea *(Cicer arietinum)* suffered most with the

Table 1: Area ('000 ha), production ('000 t), and yield (kg ha^{-1}) of major grain legumes in rice-wheat growing states of India.

	1960-61			1993-94		
Crop/State	Area	Production	Yield	Area	Production	Yield
Pigeonpea						
Uttar Pradesh	652	886	1358	530	550	1038
Punjab	0.8	0.2	261	11	10	909
Haryana	-	-	-	50	50	1000
Madhya Pradesh	3%	341	861	450	440	977
Bihar	186	111	596	80	80	1000
Rajasthan	24	7	292	19	7	356
West Bengal	34	21	617	6	5	855
Chickpea						
Uttar Pradesh	2552	1831	717	1030	940	913
Punjab	945	681	721	20	20	1000
Haryana	1444	1276	884	40	40	1000
Madhya Pradesh	1498	862	575	2500	2080	832
Bihar	542	324	597	130	140	1076
Rajasthan	1377	920	668	1220	750	615
West Bengal	150	87	580	20	10	500
Groundnut						
Uttar Pradesh	210	175	833	150	130	866
Punjab	-	-	-	8	8	1000
Haryana	-	-	-	2	2	739
Madhya Pradesh	385	274	712	280	250	893
Bihar	-	-	-	5	5	980
Rajasthan	102	51	500	290	210	724
West Bengal	-	-	-	17	21	1224

Source: Different issues of Agricultural Situation in India.

expansion of RWCS as the area and production of this crop decreased in all the rice-wheat growing states except Madhya Pradesh. Area and production of groundnut *(Arachis hypogaea)* also decreased in Uttar Pradesh and Madhya Pradesh, although the status of this crop as revealed by area and production improved in Rajasthan. These data clearly explain shrinkage in the area and production of legume crops in rice-wheat growing states. With knowledge of the beneficial role of legumes in sustaining high productivity of RWCS, the present grim scenario of legumes in rice-wheat growing areas needs to be changed. Inclusion of legumes in RWCS assumes further significance in present-day agriculture because the availability of organic sources of plant nutrients is inadequate.

PROSPECTS OF INCLUDING LEGUMES AND ENHANCING THEIR RESIDUAL EFFECT IN RWCS

Research evidence suggests that large scope exists for inclusion of legumes in rice-wheat sequence as intercrops, catch crops, green fodder crops, or as green manure. Alternatively, in a long-term perspective, one of the cereal crops can also be substituted intermittantly with a legume crop which, generally acts as a soil health restorer on account of its ability to fix atmospheric N and utilize soil nutrients from deeper soil layers through the tap root system. The amount of N_2 fixed by legumes varies from crop to crop and also due to cultural practices and edaphic conditions. It largely depends on water supply, nodulation, photoperiod, crop-growth duration, crop management practices including tillage and fertilizer N application, and soil N fertility (Table 2). A large part of N_2 fixed by the legume plants is utilized for building up of their own vegetative parts and development of grains. But a considerable amount of N, which varies in different legumes, is also released into the soil and is made available to the succeeding crop (Table 3). However, fodder legumes generally contribute more residual N than grain legumes. Symbiotic N_2-fixation by legumes can be made more effective by inoculation with appropriate species of *Rhizobium.* In a country where the average consumption of plant nutrients through chemical fertilizers is very low, the residual fertility build-up due to grain legumes is obviously a major contribution which must be fully exploited.

Agronomic Prospects

A large number of experiments have been conducted on the possibility of introducing legumes in RWCS. These experiments carried out under the All India Coordinated Agronomic Research Project (AICARP) of the Indian Council of Agricultural Research (ICAR) and other programs in different agroclimates have indicated the beneficial effects of legumes (grown as intercrops, catch crops, substitute crops for grain and fodder, or green manure) on the productivity of this system and soil fertility. The grain

Table 2: Amount of nitrogen (N) fixed by different grain legumes.

Crop	Location	N fixed (kg ha^{-1})	Method	Treatment variable
Groundnut	Australia	37-133	^{15}N	Water supply
	Brazil	68-116	^{15}N	Inoculation
	Ghana	32-134	N-diff	Cultivar
	India	109-152	^{15}N	Cultivar
Pigeonpea	India	68-88	^{15}N	Season
Soybean	Brazil	85-154	^{15}N	Site/season
	Indonesia	26-33	^{15}N	Rotation
	Nigeria	15-125	^{15}N	Inoculation
	Thailand	17-450	^{15}N	Cultivar
Common bean	Brazil	3-32	^{15}N	Cultivar
	Kenya	17-57	^{15}N	Phosphorus
Cowpea	Brazil	9-51	^{15}N	Site/season
	Indonesia	12-22	^{15}N	Rotation
	Kenya	24-39	^{15}N	Phosphorus

Source: Peoples and Herridge (1990).

Table 3: Amount of nitrogen (N) released into the soil by various legumes.

Crop	N released into the soil (kg ha^{-1})
Black gram *(Vigna mungo)*	38.3
Mung bean *(Vigna radiata)*	34.5
Cowpea *(Vigna unguiculata)*	50.3
Horse gram *(Macrotyloma uniflorum)*	27.1
Lentil *(Lens culinaris)*	32.8
Pea *(Pisum sativum)*	59.4
Khesari *(Lathyrus sativus)*	54.9
Cluster bean *(Cyamopsis tetragonoloba)*	55.7
Sunn hemp *(Crotalaria juncea)*	75.0
Berseem *(Trifolium alexandrinum)*	54.2
Dhaincha *(Sesbania aculeata)*	68.9

Source: Singh et al. (1981).

legumes grown as a third crop in the system, however, showed inconsistent effects (Singh et al. 1994).

Legumes as Intercrops

Several legumes such as pigeonpea, black gram *(Vigna mungo),* mung bean *(Vigna radiata),* groundnut, and soybean *(Glycine max)* are ideal intercrops in upland direct seeded rice (Lal and Singh 1990). Besides increasing the total productivity of the system, legumes play an important role in economizing the use of resources, particularly N fertilizer. The potential of legumes as intercrops in RWCS has not yet been fully exploited.

Legumes as Catch Crops

The most feasible way of including legumes in RWCS without decreasing land area of the cereal crops is to grow legumes as catch crops. This, however, depends on the duration of rice and wheat varieties and the legume crops to be introduced. In RWCS, medium-duration rice varieties followed by wheat varieties suited for normal sowing in eastern India and late sowing in northern India have been found the best option as far as total grain productivity of the system is concerned. In this type of varietal combination, practically there is no scope for inclusion of winter legumes between rice harvesting and wheat sowing. However, the period between wheat harvesting and rice planting can be well utilized for growing short-duration summer legumes provided irrigation facilities are available during this season (Fig. 1). Otherwise, this period is left unutilized and the precious natural resources of land and sunshine remain untapped. A summer legume (pulse) variety maturing in 60-70 days provides additional economic return. Incorporation of legume residues left after harvesting the grain benefits the succeeding rice crop as it reduces fertilizer N requirement.

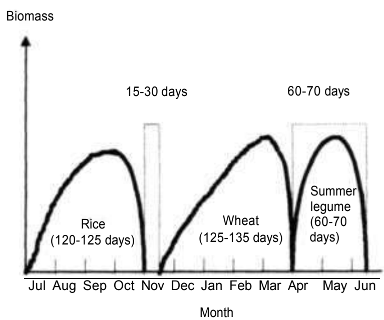

Figure 1: Diagramatic presentation of the scope for inclusion of legumes in rice-wheat cropping system.

Experiments at Masodha, Varanasi, and Ludhiana indicated that inclusion of mung bean in rice-wheat system enhanced the total productivity and net returns as compared to rice-wheat system alone (Fig. 2) (Singh et al. 1994). De (1980) reported that rice yield increased when preceded by legumes and was 5.09 t ha^{-1} after cowpea *(Vigna unguiculata),* 4.78 t ha^{-1} after mung bean, and 4.60 t ha^{-1} after black gram compared with 3.52 t ha^{-1} obtained after fodder maize *(Zea mays).* In other studies, the yield of rice in rice-wheat system generally remained higher when preceded by mung bean (Meelu et al. 1992). Antil et al. (1989), on the basis of a 2-yr study in mildly alkaline loam soil of Haryana, reported that preceding legume crops not only increased the yield of rice but also made it possible to curtail the fertilizer N dose. The optimum doses of N in rice were 73.6 kg ha^{-1} after

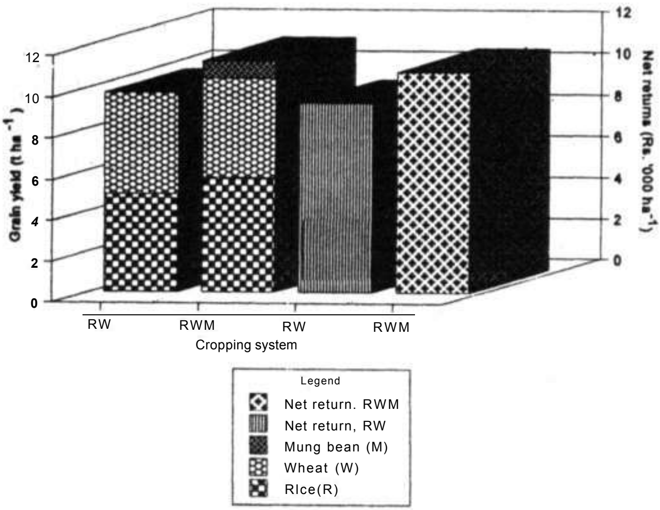

Figure 2: Effect of grain legumes on the productivity and profitability of rice-wheat cropping systems in India (average of three locations, Masodha, Varnasi, and Ludhiana).

Sesbania, 66.3 kg ha^{-1} after mung bean, 152.4 kg ha^{-1} after maize, and 151.6 kg ha^{-1} after fallow.

Results contradicting the beneficial effect of short-duration grain legumes have also been evident at some other locations. Mung bean and black gram grown during summer markedly decreased rice yield at Ranveer Singh Pura (R.S. Pura) (Table 4). Based on these findings, it is speculated that growing grain legume as a third crop does not always improve the system productivity and conclusions on the benefits accrued through grain legumes cannot be drawn without defining the growing environment and cultural practices.

Table 4: Effect of grain legumes on rice-wheat productivity in India during 1985-1992.

	Grain yield (t ha^{-1})		
Location/Cropping system	Summer	Monsoon	Winter
R.S. Pura (Ranveer Singh Pura)			
Rice-wheat		537	3.77
Rice-wheat-mung bean	0.19	4.99	3.75
Rice-wheat-black gram	0.55	4.34	3.85
Varanasi			
Rice-wheat	-	326	4.54
Rice-wheat-mung bean	0.39	3.51	4.46

Source: AICARP Annual Reports (1985-92), Project Directorate for Cropping Systems Research, Modipuram, Meerut, India.

Legumes as Substitute Crops

Substitution of rice or wheat crops with legumes in rotation has shown promise in the experiments carried out in AICARP (Singh et al. 1994). However, substitution of the rice or wheat crop largely depends on the nature of stresses witnessed in different agroecologies. For instance, in the state of Punjab where depletion of the water table is emerging as a serious problem, there is scope for substituting rice with pigeonpea. Similarly, weed *(Phalaris minor)* infestation in wheat in the rice-wheat growing areas of northwestern plains and Terai region has increased enormously and has emerged as a major threat to sustainability of the system productivity. In these areas, berseem *(Trifolium alexandrinum)* can be grown as a break crop. In eastern India, where productivity of wheat is generally low because of climatic constraints particularly higher thermal regimes, wheat needs to be substituted with chickpea, lentil (*Lens culinaris),* pea *(Pisum sativum),* and groundnut. Another significant factor determining substitution of one of the cereals with a legume crop is the moisture regime and level of soil submergence, more so during monsoon. In India, nearly 85% of the rice soils are lowlands which are characterized by prolonged water stagnation due to several reasons. These areas do not permit any substitution of rice with legumes. The scope for substitution in monsoon, therefore, exists only in the regions where upland/irrigated rice is grown, though such areas are spread mainly in Punjab, Haryana, and western Uttar Pradesh, and constitute only 15% of the total area under rice. However, wheat can successfully be substituted with winter legumes.

Reports from different parts of the country indicated that inclusion of legumes in rice-wheat system as a substitute crop increased the productivity of rice. Extensive studies on the comparative performance of rice-wheat vs. rice-legume or legume-wheat systems at several locations in the Cropping Systems Research Project are being carried out and interesting results have been obtained. In a study involving rice-wheat and rice-pulse systems with recommended fertilizer application for both crops in the sequence, rice productivity was consistently higher in rice-pulse than in rice-wheat system at all the locations (Hegde 1992). The pulses involved were lentil (Pantnagar), chickpea (Varanasi and Kanpur), and black gram (Bhubaneswar). The increase in productivity of rice was higher with lentil than with other pulses (Table 5). With pulse crops such as lentil at Pantnagar, even with 25% reduced fertilizer application it was possible to harvest as high yield of rice as with 100% fertilizer use in rice-wheat sequence. While substitution of wheat with a pulse resulted in enhanced productivity of rice because of residual effect, substitution of rice with a pulse failed to leave any carry over effect on the succeeding wheat crop. Results of the experiments carried out under Cropping Systems Research Project clearly indicated that substitution of wheat with pea at Ludhiana and chickpea at Kharagpur increased the yield of rice as well as total productivity of the system (Table 6). On the other hand, substitution of rice by pigeonpea and mung bean at these locations did not improve wheat productivity but resulted in marked

Table 5: Productivity of rice in rice-wheat and rice-pulses cropping systems.

Cropping system (% of recommended NPK applied to each crop)	Rice yield (t ha^{-1})			
	Pantnagar[1]	Varanasi[2]	Kanpur[3]	Bhubaneswar[4]
Rice-wheat (100) (100)	3.94	3.65	3.61	3.54
Rice-pulse (100) (100)	4.30	3.84	3.80	3.63
Rice-pulse (75) (100)	4.14	3.13	3.01	3.02

[1]Lentil in rice-pulse system; data is average of 5 years.
[2]Chickpea in rice-pulse system; data is average of 5 years.
[3]Chickpea in rice-pulse system; data is average of 4 years.
[4]Black gram in rice-pulse system; data is average of 3 years.
Source: Hegde (1992).

Table 6: Effect of legumes grown as substitute crops on the rice-wheat cropping system productivity in India.

Location/Cropping system	Fertilizer application (% of recommended NPK) Monsoon	Winter	Grain yield (t ha^{-1}) Monsoon	Winter	Rice/wheat equivalent
Ludhiana[1]					(Wheat)
Rice-wheat	100	100	6.33	4.97	10.97
Rice-pea	100	100	6.70	2.38	11.69
Rice-pea	75	100	6.44	2.40	11.25
Pigeonpea-wheat	100	100	1.26	5.06	7.90
Pigeonpea-wheat	100	75	1.21	4.97	7.68
Chiplima[2]					(Rice)
Rice-wheat	100	100	5.82	1.91	7.85
Rice-groundnut	100	100	5.65	2.57	13.70
Rice-groundnut	75	100	5.42	2.23	12.41
Kharagpur[2]					(Rice)
Rice-wheat	100	100	5.29	3.13	7.93
Rice-chickpea	100	100	5.61	0.98	7.82
Rice-chickpea	75	100	5.37	0.98	7.59
Mung bean-wheat	100	100	0.98	3.18	4.90
Mung bean-wheat	100	75	1.38	2.79	6.42

[1]Yield is average of three years.
[2]Yield is average of two years.
Source: Singh et al. (1994).

deterioration in total productivity of the system. At Chiplima, substitution of wheat by groundnut had no beneficial effect on the rice yield but improved the total productivity of the system as far as rice equivalent yields are concerned. Poor residual effect of monsoon pulses on succeeding wheat crop seems to be associated with slow mineralization of organic N due to low temperature during winter in rice-wheat growing areas of the country (Singh et al. 1994).

Nevertheless, for sustaining the productivity of such an exhaustive system, emphasis should be laid on the application of limiting secondary and micronutrients in addition to major nutrients. The results of the Food and Agriculture Organization of the United Nations (FAO)-Sulfur Field Trials have indicated that application of 20-30 kg sulfur ha^{-1} increased the productivity of both rice-wheat and rice-legume systems at several locations (Biswas and Tewatia 1991).

The beneficial effects of substituting wheat or rice with a legume on soil fertility have also been reported. Hegde and Dwivedi (1992b) reviewed the results of AICARP experiments and reported that as compared to rice-wheat system, substitution of wheat with pea at Ludhiana, lentil at Pantnagar, chickpea at Kanpur, black gram at Bhubaneswar, and groundnut at Chiplima resulted in a marked increase in organic carbon and available NPK when compared with rice-wheat system. The magnitude of increase, however, varied depending on the legume species and the location (Table 7). In another study conducted on sandy clay loam soil of Ranchi, removal of N by the crops in legume-wheat system was higher than that in rice-wheat system; however, P and K removal was high in the rice-wheat system (Table 8). Net balance of P and K in the soil was also high in legume-wheat system (Sahay et al. 1989). The benefit of legumes cannot be explained solely in terms of residual N but there are also other avenues of benefit. A number of factors can operate and the relative importance of each is dictated by site and agroclimate. Improvements in soil structure following legumes, breaking of cycles of cereal pests and diseases, ability to mine the nutrients from different soil layers, control of weeds, and phytotoxic and allelopathic effects of different crop residues can result in extra yield in a sequential cropping system (Sharma 1993).

Legumes as Fodder Crops

A number of leguminous fodder crops have been evaluated for the contribution which they make in meeting the N requirement of the succeeding crop in the system and it has been found that as much as 35-120 kg N ha^{-1} can be made available. The carry over of N for succeeding cereals is about 120 kg in berseem, 75 kg in *Medicago saliva,* and 35-60 kg in fodder cowpea (Singh et al. 1981). These fodder legumes yielding 40-90 t ha^{-1} green fodder offer ample scope for inclusion as break crops in RWCS. The number of rice-wheat cycles after which a break crop of fodder legume is to be introduced needs to be investigated through detailed experimentation.

Table 7: Effect of rice-pulse/oilseed systems on soil fertility in India.

Treatment/ Cropping system (% of recommended NPK)	Organic carbon (%)	Available nutrient (kg ha^{-1})		
		N	P	K
Ludhiana				
Rice (lOO)-wheat (100)	0.64	338.2	82.3	95.0
Rice (100)-pea (100)	0.73	344.9	32.3	87.0
Rice (75)-pea (100)	0.74	337.9	58.4	83.4
Initial value	0.39	348.0	14.6	168.0
Pantnagar				
Rice (100)-wheat (100)	1.18	-[1]	37.4	167.8
Rice (lOO)-lentil (100)	1.19	-	41.4	177.9
Rice (75)-lentil (100)	1.19	-	39.2	191.5
Initial value	1.20	248.0	33.1	181.0
Kanpur				
Rice (100)-wheat (100)	0.24	-	12.6	132.2
Rice (lOO)-chickpea (100)	0.28	-	14.6	160.8
Rice (75)-chickpea (100)	0.32	-	18.6	196.4
Initial value	0.23	122.0	11.0	304.0
Bhubaneswar				
Rice (lOO)-wheat (100)	0.67	-	23.5	220.0
Rice (lOO)-black gram (100)	0.57	-	21.5	245.0
Rice (75)-black gram (100)	0.73	-	19.0	230.0
Initial value	0.68	320.0	22.0	205.0
Chiplima				
Rice (lOO)-wheat (100)	0.66	-	18.5	175.0
Rice (lOO)-groundnut (100)	0.45	-	17.5	195.0
Rice (75)-groundnut (100)	0.48	-	16.0	185.0
Initial value	-	-		-

[1] Not reported.

Source: Hedge and Dwivedi (1992b).

Legumes as Green Manures

Before the advent of mineral fertilizers, green manuring was considered as an indispensable practice for restoring soil fertility. Green manuring with fast growing legumes such as *Sesbania aculeata,* sunn hemp *(Crotalaria juncea),* and cowpea as a source of organic manure had been an age-old practice in rice-wheat growing areas of India. However, with the intensification of the system in these areas through double cropping of rice and wheat in sequence, available time gap became a major limiting factor and farmers resorted to other alternative nutrient sources (e.g., chemical fertilizers) and the practice of green manuring was almost given up. But in recent years, with indication of declining trend in productivity due to continuous use of chemical fertilizers, there has been a revival of interest in green manuring. Studies have shown that green manure N was generally as effective as fertilizer N (Meelu and Morris 1984). About 6.3 million ha of area in India is estimated to be under green manuring but the area actually green manured in RWCS

Table 8: Status of NPK in soil under different crop sequences after harvest of winter crops at Ranchi, India, 1985-86.

Crop sequence	Addition through fertilizers (kg ha^{-1})	Crop removal (kg ha^{-1})	Balance (kg ha^{-1})	Removal/ addition ratio
N				
Rice-wheat	140	92.2	+47.8	0.7
Soybean-wheat[1]	120	124.1	-4.1	1.0
Groundnut-wheat[1]	125	115.1	+9.9	0.9
P				
Rice-wheat	35	16.6	+18.4	0.5
Soybean-wheat[1]	48	12.8	+35.2	0.3
Groundnut-wheat[1]	44	16.7	+27.3	0.4
K				
Rice-wheat	37.4	132.1	-94.8	3.5
Soybean-wheat[1]	54	55.1	-1.2	1.0
Groundnut-wheat[1]	41.5	84.9	-43.4	2.0

[1] No information on the amount of nitrogen fixed by legumes.

Source: Sahay et al. (1989).

is not precisely known. Use of green manure in RWCS has been in practice only during the past 15 years and advantages of growing a green manure crop after wheat harvest are well established (Hegde 1992).

Studies on green manuring have established it to be a feasible practice to enhance the productivity of rice-wheat system and soil productivity as well. About 60-70 t ha^{-1} of fresh biomass is added to the soil system by green manuring during summer (May-June) after harvesting of wheat. At Pantnagar, *Sesbania aculeata* proved the most efficient green manure crop as the yield of rice and wheat was highest with *Sesbania* as compared to other green manure crops (Table 9). Experiments carried out at several other locations under AICARP have distinctly established the advantages of introducing green manure crop of *Sesbania* in rice-wheat system as a

Table 9: Effect of different summer green manure crops on yield (t ha^{-1}) of rice and wheat in rice-wheat sequence at Pantnagar, India, during 1983-87.

	Site I		Site II	
Crops	Rice	Wheat	Rice	Wheat
Sesbania	6.54	3.75	7.14	4.12
Sunn hemp	5.99	3.35	6.68	3.92
Cowpea	5.77	3.20	6.55	3.80
Control	-[1]		6.14	3.52
CD (0.05%)	0.428	NS[2]	0.22	0.32

[1] - = treatment not included.

[2] NS = not significant.

Source: Pandey and Rana (1992).

supplement to inorganic fertilizers (Table 10). Green manuring along with recommended levels of fertilizers had a beneficial effect on the yield of both the crops and increased the total productivity of the system by 18% at Ludhiana, 10% at Pantnagar, 6% at Varanasi, 8% at Kanpur, and 4% at Bhubaneswar. It was further observed that at Pantnagar, fertilizer application to rice-wheat system could be curtailed by 50% due to summer green manuring without any adverse effect on total grain production.

Table 10: Effect of green manuring with *Sesbania* (GM) on the productivity of rice-wheat system.

Location/Crop (% of recommended NPK)			Grain yield ($t\ ha^{-1}$)		
Monsoon	Winter	Summer	Rice	Wheat	Total
Pantnagar (average of 4 years)					
Rice (100)	Wheat (100)	-	4.16	4.50	8.67
Rice (100)	Wheat (100)	GM	4.69	1.85	6.54
Rice (75)	Wheat (75)	GM	4.65	4.29	8.94
Ludhiana (average of 4 years)					
Rice (100)	Wheat (100)	-	5.81	3.82	9.63
Rice (100)	Wheat (100)	GM	6.72	4.88	11.60
Rice (75)	Wheat (75)	GM	5.48	3.74	9.22
Varanasi (average of 3 years)					
Rice (100)	Wheat (100)	-	3.54	3.07	*652*
Rice (100)	Wheat (100)	GM	3.91	3.00	6.91
Rice (75)	Wheat (75)	GM	3.44	2.62	6.07
Kanpur (average of 3 years)					
Rice (100)	Wheat (100)	-	3.63	3.58	7.21
Rice (100)	Wheat (100)	GM	3.96	3.80	7.76
Rice *(75)*	Wheat (75)	GM	3.50	3.34	6.84
Bhubaneswar (average of 2 years)					
Rice (100)	Wheat (100)	-	3.80	2.76	6.55
Rice (100)	Wheat (100)	GM	3.82	2.94	6.76
Rice (75)	Wheat (75)	GM	3.19	2.34	5.53

Source: Hegde and Dwivedi (1992b).

Age of the green manure crop and time of its incorporation in the soil also affect its manurial efficiency. Beri and Meelu (1981) reported that in sandy loam soils of Ludhiana, incorporation of a 60-day-old crop of *Sesbania,* one day before transplanting of rice was as good as burying the crop 15 days before the transplanting as per earlier practice.

Green manuring resulted in benefit equivalent to 60 kg N ha^{-1} or more of fertilizer N for rice while little or no residual effect was observed on the yield of succeeding wheat crop (Goswami et al. 1988; Kolar and Grewal 1988; Narang et al. 1989; Tiwari and Sharma 1989; Palaniappan et al. 1990; Pandey and Dwivedi 1990; Narang and Bhandari 1992). Goswami et al.

(1988) using ^{15}N indicated that green manuring contributed 4.7-5.6% of total N taken up by rice and 1.9-4.8% by succeeding wheat depending upon the rate of fertilizer applied to rice. At 60 and 120 kg N ha^{-1}, the N recovery by rice-wheat system was 56.2% and 61.4% respectively after summer fallow and 58.4% and 60.6% respectively after green manuring. Tiwari et al. (1980), however, reported the carry-over effect of green manuring on succeeding wheat in addition to its direct effect on rice in a partially reclaimed saline-sodic soil (see Table 8 in Rego et al., 1998). Green manure substituted as much as 50% N needs of rice in rice-wheat system without any reduction in yield at Ludhiana while at Kalyani substitution up to 50% resulted in 7% higher yield compared with fertilizer alone (Table 11). At Kanpur, data of 5 years indicated that there was 25% saving in fertilizer dose to wheat when 25% N need of preceding rice was substituted by green manure. Bhandari et al. (1989) reported that combined use of green manure and chemical fertilizer also results in build-up of soil organic carbon and available nutrients except that of zinc (Table 12).

Table 11: Effect of green manuring (GM) on the productivity of rice-wheat system in India.

Location/Treatment		Grain yield (t ha^{-1})		
Rice	Wheat	Rice	Wheat	Total
Ludhiana (average of 6 years)				
100% NPK	100% NPK	6.29	4.57	10.86
50% NPK + 50% N (GM)	100% NPK	6.21	4.50	10.71
Kanpur (average of 5 years)				
100% NPK	100% NPK	3.95	4.64	8.59
75% NPK + 25% N (GM)	75% NPK	3.92	4.49	8.41
Kalyani (average of 3 years)				
100% NPK	100% NPK	3.71	2.75	6.46
50% NPK + 50% N (GM)	100% NPK	3.94	2.98	6.92

Source: AICARP Annual Reports (1980-89), Project Directorate for Cropping Systems Research, Modipuram, Meerut, India.

Table 12: Effect of green manuring (GM) on available nutrients after three cycles of rice-wheat system at Ludhiana, India during 1983-86.

Treatment (% of recommended NPK)		OC[1]	N	P	K	Fe	Mn	Cu	Zn
Rice	Wheat	(%)	kg ha^{-1}			ppm			
100%	100%	0.35	148	13.7	107	11.3	9.2	0.96	1.76
100% + 50% N (GM)	100%	0.39	151	15.0	120	12.6	9.5	0.95	1.77
Initial status		0.31	143	11.2	101	9.6	9.2	0.80	1.96

[1] Organic carbon.

Source: Bhandari et al. (1989).

Multipurpose Legume Shrubs

In the farming situations where farmers are reluctant to spare their meager land resources and inputs for growing green manure crops, fresh lopping of perennial leguminous trees such as *Gliricidia, Casuarina, Leucaena,* and *Sesbania sesban* grown in hedge rows (alleys) and on field bunds may be used for incorporation into the soil as source of N (Kundu et al. 1991). Green leaf manure applied before transplanting rice releases more N than farm yard manure (Chatterjee et al. 1979). In addition to improving soil health, these multipurpose legume shrubs also provide nutritious fodder for animals (Gangwar et al. 1994). Despite all the benefits, the scope for large-scale adoption of alley cropping in RWCS is limited to upland marginal lands.

Genotypic Prospects

Development of early-maturing genotypes has made it possible to include legumes in cropping systems as a catch crop, substitute crop, or an intercrop. In 1960s an early maturing variety of pigeonpea (T 21) was developed for double cropping but later it was observed that either due to little delay in its planting or prolonged monsoon rains, this variety did not mature within desirable period and fields were not vacated on time for wheat sowing. Therefore, in subsequent years, efforts were made to develop varieties with 140-150 days maturity. A large number of pigeonpea varieties such as UPAS 120, Pusa Ageti, Pusa 74, Pusa 84, Pusa 33, Manak, ICPL 151, and IT 6 are now available which can be easily substituted for rice in rice-wheat system in irrigated belt of northern India. These varieties can yield 1.5-2.0 t ha^{-1} and the succeeding wheat crop is also benefitted due to residual effect (Yadav 1991).

In areas where wheat can be substituted with legumes, chickpea genotypes such as BG 261 and Radhey can be used. These genotypes are amenable to late planting and offer good scope for rice-chickpea sequential cropping in place of rice-wheat (Yadav 1991).

The development of short-duration (60-65 days) and synchronous varieties of mung bean and black gram proved a boon for catch cropping and as a consequence the area under spring/summer legumes increased manifold during the past decade (Yadav 1991). The early-maturing varieties of mung bean recommended for spring or summer cultivation in rice-wheat growing areas of northern India are T 44, Pusa Baisakhi, PS 16, K 851, PDM 11, PDM 54, and Pusa 105. The black gram varieties suitable for spring cultivation after harvest of wheat are T 9, Pant U 19, Pant U 30, and UG 218. Most of these new genotypes are field-tolerant to yellow mosaic virus. Improved varieties of legumes have been developed for different zones (Table 13). These varieties possess fairly good tolerance/resistance to major diseases and pests and are suitable for inclusion in the intensive cereal-cereal cropping systems.

Table 13: Improved varieties of legumes for rice-wheat growing zones in India.

Crop	Northwest plain zone	Northeast plain zone	Central zone
Chickpea	Pusa 209, Pusa 256, C 235, PBG 1, Gaurav, SC 1, Pant G 114	Pusa 209, Pusa 240, Pusa 256, Avrodhi, K 850, SG 2	Pusa 417, VDNG 154, G 12, Vijay, JG 62
Pigeonpea	Pusa 33, AL 15, UPAS 120, Manak, ICPL 151, Paras	Bahar, Sharada, T 21, Laxmi, BR 61, Birsa	ICPL *77,* ICPL 87, BSMR 175, TT 6
Mung bean	ML 32, ML 237, Pant M 3, PS 16, Pusa 105	PDM 54, S 8, PS 10, Pusa 105, Pant M 3, Narendra Moong 1, Amrit	PDM 11, PS 7, Pusa 105, K 851, BM 4
Black gram	Mash 338, Mash 218, T 9, Krishna	PDU 1,PDU88, Pant U 19, Narendra Urd 1, T 65, Naveen	Pant U 30, TAU 1, TAU 2, TPU 4
Lentil	DPL 25, L 4076, Pant L 406, L 9-12, Sapna	Pant L 639, T 36, Malika, Arun, L 9-12	Lens 830, JL 1, Pant L 639, L 4076
Pea	Swastik, Field Pea 48, Aruna, Pant P 5, Rachna, Shiksha	Rachna, Malviya, Matar 2, Swarnarekha	Rachna, KPMR 10, JP 4
Cowpea	C 152, Amba, Rc 19, RMG 44	C 152, Amba, B 38, Gomti	C 152, B 240, Amba, B 38

KNOWLEDGE GAPS AND FUTURE RESEARCH PRIORITIES

Inclusion of legumes in RWCS holds great promise in sustaining high production levels of the system as well as long-term soil health, although constraints such as high vulnerability of legumes to diseases and pests, extra cost and time required for a short-duration grain legume or green manure crop limit their large-scale adoption. Data generated yet on this aspect can be utilized to develop useful recommendations for different rice-wheat growing regions. The important future research strategies are outlined.

- At present, concern about deterioration/stagnation in productivity of rice-wheat system is more based on concepts and hypotheses. Quantitative information on this aspect is quite scanty. There is a need to create a strong database on the productivity of the system and related soil, environmental, and social factors. This will facilitate identifying target areas and factors for future research.

- The detailed status of legumes in rice-wheat growing areas of the country is not very well known. Pragmatic information on the area, production, and productivity of legumes grown as catch crops, substitute crops, or green manure in rice-wheat system need to be collected through sample surveys and other advanced diagnostic tools such as geographic information systems (GIS).
- Expansion of rice-wheat system in non-traditional areas of northwestern plains has resulted in groundwater depletion. Quantitative data on the magnitude of this problem is, however, not available. There is an urgent need to identify areas where depletion of groundwater is emerging as a serious production constraint. In these areas, diversification of the system through legumes that require less water should be advocated.
- Continuous rice-wheat cropping is known to build up particular weed flora and pests. The cycle needs breaking with one or the other legume crops. Depending on severity of the problem and the growing season, thoroughly planned medium- and long-term experiments are needed in different agroecologies to optimize the number of rice-wheat cycles after which a break crop of legume needs to be introduced for eradication of weeds and pests.
- Where irrigation facilities are available, green manuring could be advocated. In rice-wheat systems, summer green manuring merits special attention as this practice fits well in the system in Uttar Pradesh and Bihar. So far, concerted efforts have not been made for popularization of this practice.
- Present information suggests that the need for fertilizer N can be partially fulfilled through alternate sources such as growing of grain legumes and green manuring. The effect of these resources need to be quantified so that the dose of chemical fertilizers could be curtailed.
- While breeding legume varieties the system component should be given due consideration. Legume varieties with desirable traits for rice-wheat system can easily be introduced in the system without any adverse effect on the productivity and profitability.

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Recommendations

Recommendations

The participants were divided into three separate groups—winter grain legumes, summer and rainy season grain legumes, and green manure and forage legumes—to discuss and make recommendations on issues related to future research needs and their implementation.

FUTURE RESEARCH NEEDS OF WINTER GRAIN LEGUMES IN RICE AND WHEAT CROPPING SYSTEMS

The subject was discussed by a group chaired by Dr. Masood Ali (India). The other members of the group were: Dr. M.A. Razzaque II (Bangladesh), Ms. S. Bhattarai (Nepal), Dr. Zahir Shah (Pakistan), Dr. O.P. Rupela (ICRISAT, India), Dr. S.P. Wani (ICRISAT, India), and Dr. P.K. Joshi (ICRISAT, India). A summary of the conclusions and recommendations made is presented.

Constraints in Adopting Viable Technologies

(a) Lack of adequate production of seeds of improved varieties of winter grain legumes specially suited for rice-based cropping systems, i.e., for late planting situations.

(b) Low stability in yield and production due to biotic and abiotic stresses; hence economically not competitive.

(c) Planting of winter grain legumes is normally delayed due to late harvest of preceding rice; thus they are particularly prone to biotic stresses such as *Helicoverpa* damage.

(d) Inadequate price support mechanisms to alleviate effects of market price fluctuations.

Critique of Existing Knowledge

(a) There was little breeding effort for winter grain legumes particularly suited for late planting situations, hence, lack of varieties of chickpea, lentil, peas, and other legumes appropriately adopted to late planting in rice-based systems.

(b) Inadequate information on management technologies for including legumes in rice-based cropping systems, and little dissemination to farmers of existing knowledge.

Knowledge Gaps

There is a lack of knowledge on non-nitrogen (N) effects of winter grain legumes on the succeeding crops. There is a need to characterize this effect in terms of soil physical, chemical, and biological properties.

Researchable Issues

(a) Identification and characterization of new niches for legumes in rice-based cropping systems. It is important to target legumes to suitable niches as the Indo-Gangetic Plain (IGP) is a vast area. For example in India, the legume yields (chickpea in particular) are generally better in the northeast plain zone compared to the northwest plain zone. We should therefore identify areas where there is more potential for legumes so as to better prioritize research and development (R & D) efforts.

(b) Development of varieties amenable for late planting and also having high yield potential under existing water and nutrient resources in rice-based systems. For example, chickpea tends to produce more vegetative growth but with low harvest index under high input (water and nutrient) conditions of rice-based systems. Thus, attempts should be made to increase the harvest index on a high biomass base.

(c) Integrated weed management: Weed flora change qualitatively and quantitatively between upland and rice-based systems. Since grain legumes (e.g., lentil in western Uttar Pradesh and bordering Nepal) are grown as relay crops with rainy season rice, there is a need for integrated weed management considering declining soil moisture and soil physical conditions.

(d) Integrated nutrient management in rice-winter grain legume systems: So far, fertility management trials have mostly been confined to individual crops. Hence, there is a need to work out optimum nutrient requirements for rice-based cropping systems involving legumes, through the following activities:

   (i) Calculate nutrient budgets of rice-based systems involving winter legumes either as a sole crop or mixed or intercropped with wheat. This will provide knowledge of the sustainability of the system, with or without legumes.

   (ii) Management of rice residue to maximize its return to the soil.

   (iii) Establish optimum N requirements for legumes grown with and without crop residues.

   (iv) Phosphorus (P) management in the system: As P is a costly input, we need to establish how to optimally meet P requirements of the system. It has been shown that wherever double cropping is practiced it is better to apply P to the winter crop, so that its efficiency is enhanced for the rainy season rice because of optimum moisture and temperature.

(v) Isolation of efficient *Rhizobium* strains: Because of flooding/anaerobic conditions during the rice-growing season, the rhizobial population is adversely affected. Hence, there is a need to isolate effective *Rhizobium* strains that perform relatively better in soils where rice is grown annually,

(vi) Improve techniques for establishment of legumes especially under relay cropping systems,

(vii) Intercropping of winter legumes with wheat especially under rainfed conditions: Growing a grain legume after wheat (e.g., summer mung bean) may not be liked by farmers due to the extra labor requirement before the rainy season. Mixed cropping of berseem and wheat is common in some areas. Other legume options for intercropping or mixing with wheat need to be explored.

Quantification of N_2 Fixed

There is a need for systematic trials to determine N_2 fixed by winter grain legumes verified by ^{15}N-based methods.

Long-term Trials

There have been long-term trials to test the effect of single or multiple nutrient application on soil fertility but very little work has been done on legume effects vis-a-vis sustainability of the system. Hence, long-term fertility experiments should be reviewed before initiating long-term experiments on rice-legume systems in different agroecological zones.

Economic Analyses of the Systems

Economic analysis should cover both direct and indirect benefits of legumes in the cropping system. Residual benefits of legumes need to be costed.

FUTURE RESEARCH NEEDS OF SUMMER AND RAINY SEASON GRAIN LEGUMES IN RICE AND WHEAT CROPPING SYSTEMS

Summer Legumes—Researchable Issues

The subject was discussed by a group chaired by Dr. R.L. Yadav (India). The other members of the group were: Dr. Delowara Khanam (Bangladesh), Dr. S.P. Pandey (Nepal), Dr. A. Satyanarayana (India), Dr. I.P.S. Ahlawat (India), Dr. Y.S. Chauhan (ICRISAT, India), Dr. Nuguyen Thi Lien Hoa (Vietnam), Dr. C. Johansen (ICRISAT, India), Dr. M. Fakhrul Islam (Bangladesh), Dr. T.J. Rego (ICRISAT, India), Dr. J.V.D.K. Kumar Rao (ICRISAT, India), and Dr. K. Thedchana Moorthy (Sri Lanka). The constraints of summer legumes in rice and wheat cropping Systems (RWCS) are: (1) asynchronous maturity; (2) moisture stress; (3) poor crop establishment;

(4) nutrient management; (5) equipment for harvesting; (6) pre-harvest sprouting due to onset of rains; (7) yellow mosaic virus; (8) pod borer; (9) weed control; (10) appropriate variety (short-duration and heat-tolerant); (11) inadequate biological nitrogen fixation (BNF) capacity and lack of heat-resistant *Rhizobium* inoculants; and (12) stray cattle. The grain legumes considered important in the IGP are:

Bangladesh: mung bean, black gram, cowpea, groundnut, pigeonpea, soybean;

India: black gram, mung bean, cowpea, short-duration pigeonpea;

Nepal: mung bean, pigeonpea, soybean, groundnut, black gram, cowpea;

Pakistan: mung bean, black gram.

For countries outside the IGP, but represented in these discussions, the grain legumes considered important are:

Sri Lanka: cowpea, mung bean, black gram, groundnut, soybean;

Vietnam: groundnut, soybean, mung bean.

The researchable issues were then broadly grouped under short-term and long-term issues and prioritized as urgent, necessary, and desirable. Developmental and extension issues were also identified. They are:

Short-term Issues

(a) Urgent:
- (i) Water management.
- (ii) Development and introduction of extra-short-duration (50-55 days) varieties.

(b) Necessary:
- (i) Nutrient management of legumes in rice-wheat cropping systems.

(c) Desirable:
- (i) Development of high temperature tolerant legume cultivars.
- (ii) Control of diseases and pests through management practices.

Long-term Issues

(a) Urgent:
- (i) Development of extra-short-duration (50-55 days), high-yielding, input responsive, heat-, disease-, and pest-resistant varieties suitable for RWCS.

(b) Necessary:
- (i) Establish system-based integrated nutrient and weed management practices.

(c) Desirable:
- (i) Develop legume cultivars with high BNF, capacity in high-input RWCS.
- (ii) Initiate research to separate 'N' and 'non-N' benefits of legumes on the following crop.

Developmental and Extension Issues

(i) Ensure availability of canal water during summer for cultivation of summer legumes.

(ii) Ensure availability of quality seed and quality *Rhizobium* inoculants.
(iii) Overcome the stray cattle menace, possibly through large-scale cultivation of summer legumes in the area.
(iv) Popularize summer legume cultivation by supplying leaflets or brochures, and organizing field demonstrations and radio and television programs.

Rainy Season Legumes—Researchable Issues

Short-term Issues

Urgent:
(i) Weed control practices.
(ii) Planting techniques and appropriate land configuration for proper crop establishment and vegetative growth.

Desirable:
(i) System-based nutrient management.
(ii) Integrated pest management (but urgent for pigeonpea).

Long-term Issues

Urgent:
(i) Develop short-duration, high-yielding (a minimum yield of 2t ha^{-1}), waterlogging-, disease-, and pest-resistant legume genotypes suitable for sole and intercropping systems.

Necessary:
(i) Develop legume genotypes that produce reliable yields in high input systems.
(ii) Establish integrated nutrient management practices.
(iii) Develop integrated pest and disease management practices.

Desirable :
(i) Establish suitable planting patterns for intercropping systems.
(ii) Develop equipment for efficient and economical harvesting and grain processing.

Developmental and Extension Issues

(i) Ensure availability of quality seed and quality *Rhizobium* inoculants.
(ii) Seed processing.
(iii) Make vigorous efforts to disseminate information on improved varieties and their management through extension agencies and on-farm demonstrations.

It was proposed that the National Agricultural Research Systems (NARSs) should either incorporate the researchable issues in their on-going legume research programs, or re-orient existing research programs accordingly. If additional funding is required, then collaborative research proposals with institutions such as ICRISAT may be prepared and submitted to funding agencies.

FUTURE RESEARCH NEEDS OF FORAGE AND GREEN MANURE LEGUMES IN RICE AND WHEAT CROPPING SYSTEMS

The group consisting of Dr. R.J.K. Myers (ICRISAT, India) as Chairman, Dr. Julie M. Lauren (USA), Dr. V. Beri (India), Dr. N.P. Saxena (ICRISAT, India), Dr. N.P. Rajbhandari (Nepal), Dr. B. Seeling (ICRISAT, India), Dr. M. A. Zahid (Pakistan), and Dr. M.S. Hoque (Bangladesh), discussed and prioritized the issues/constraints of forage and green manure legumes in RWCS of IGP.

It was mentioned that there could be increasing future needs for quality forage as the demand for quality milk and meat production increases in the region. Similarly, the demand for green manure legumes might increase if the prices of N fertilizers increase substantially. However, detailed statistics on the needs of RWCS of IGP for forage and green manure legumes are not available.

Constraints to Adoption of Existing Technologies for Including Legumes

(a) Legume seed availability /cost.
(b) Farmer may consider alternative options such as growing of a grain crop rather than a green manure crop as there is no immediate cash benefit from green manure.
(c) Policy changes are needed to encourage greater use of forage legumes and green manure in RWCS.
(d) Value of green manures /forages as a sustainability factor, in human health, in animal health, and overall profitability needs to be highlighted.
(e) Despite high population there is shortage of labor in the region for growing green manure or forage legumes.
(f) Lack of mechanization.
(g) Limited irrigation availability,
(h) Turnover time is often too long.
(i) Inadequate extension activities.
(j) Pest, disease, and weed carryover to the main crop.

Critique of Existing Knowledge/Knowledge Gaps

(a) Quantification of non N benefits (soil physical properties, pest + pathogen, and nutrients other than N) of green manure and forage legume crops is needed.
(b) Green manures and nutrient pumps: Deep-rooted crops could pump up nutrients from the subsoil, which are made available to the following crops of rice or wheat; this possible effect needs quantification.
(c) Efficient recycling of green manure N and that of forage legumes as affected by quality of green manure and cuttings of forage legumes

respectively. We need a better idea of the decomposition processes of residues and mineralization dynamics so that there is a better synchrony of N release and the crop demand resulting in less loss of mineralized N.

(d) Contribution of BNF: Information, particularly from farmers' fields, is needed for better quantification of the N benefits of these crops.

(e) Long-term benefits of forage legumes need to be quantified.

Researchable Issues

(a) Legume cultivars adapted to specific needs of the farmers and the region.

(b) Optimum management of the legume crop, particularly with respect to fertilizers (mainly N and P), insects, diseases, and weeds.

(c) Management of legume green manure (LGM) in the short term: Its quality vis-a-vis C/N ratio and its residual effect; its effect on pests and pathogens carryover, optimization of LGM biomass to make a positive impact on the subsequent crop.

(d) Quantification of non-N benefits and overall benefit to yield of the following crop in the short term and sustainability of the system in the long term.

(e) Cropping systems models to explore long-term benefits and effects on the dynamics of water and nutrient balances in the system, for the benefit of farmers and policy makers.

(f) Economics of growing and incorporating LGM and forages: determine the cost and the immediate (short-term) and the long-term (in terms of sustainability) benefits.

(g) True value of LGM and forages: Develop procedures for evaluating the true value, i.e., immediate value plus the long-term benefit of the legumes.

(h) Long-term trials: There is a need for medium- to long-term experiments that can be coupled with simulation modeling. Long-term trials are needed to obtain appropriate quantitative information on the dynamics and levels of soil organic matter in the system.

Target Regions

It is difficult to target any particular areas for R & D emphasis without some prior socioeconomic research to determine where the most promising areas would be for green manures and forages.

Prioritization of Future Research Needs

(a) Urgent

(i) Identification or development of LGM and forage legume cultivars adapted to specific needs.

- (ii) Quantification of non-N benefits and overall benefit to yield and sustainability in the longer term,
- (iii) Economic analysis of the true value of LGM and forages.

(b) Necessary
- (i) Management aspects of LGM and forage legumes,
- (ii) Modeling effects of LGM and forages in RWCS.

(c) Desirable
- (i) Long-term trials to understand system dynamics.

Implementation

Organizations that could be best involved:	Nepal (NARC); Pakistan (NARC); India (PAU, PDCSR); and Bangladesh (BARI).
Linkage to Rice-Wheat Consortium:	Required, as part of an overall effort.
Extra support needed:	Seed of suitable cultivars; analytical back-up; strengthening of the facilities and extra funds.
Special project or as part of an on-going program:	It is desirable to jointly establish a collaborative project for special funding. Coordination of R & D efforts on LGM and forages at the country level is needed.
Dissemination of results/ promotion of technologies:	Information currently available needs to be assembled and presented to farmers using very attractive forms (brochures, film, and demonstrations). However, there remain many information gaps with respect to optimum technologies and these need to be filled on a priority basis.

Concluding Remarks

The regional workshop on "Residual effects of legumes in rice and wheat cropping systems of the Indo-Gangetic Plain" held at ICRISAT during 26-28 August 1996 deliberated on the biological nitrogen fixation, residual effects of legumes (winter, summer, and rainy season grain legumes; forage legumes; and green manure legumes), their optimum management and prospects for legumes in member countries of the Rice-Wheat Consortium.

Legumes in general can potentially fix up to about 90% of their nitrogen (N) needs from the atmosphere. But the quantities of N_2 fixed by legumes in farmers' fields are normally much less than half the potential fixation levels, based on limited studies using ^{15}N methods. Further specific studies are needed to determine the extent of N_2-fixation by legumes in farmers' fields of rice- and wheat-based systems of the Indo-Gangetic Plain (IGP).

Legumes have been reported to substantially benefit succeeding cereals including rice and wheat in the IGP. Beneficial effects of different legumes were in the following ranges of N fertilizer equivalent: 20-60 kg N ha^{-1} in summer and rainy season grain legumes; 20-70 kg N ha^{-1} in winter grain legumes; 50-100 kg N ha^{-1} in green manure legumes; and 24-90 kg N ha^{-1} in forage legumes. The variation in N fertilizer equivalent values of different legume types reflects differences in N additions, but agronomic efficiency and N recovery are also important factors. Many workers have noted that direct effects from legumes are not solely due to N contributions. Several non-N factors have been indicated to explain the benefits of legume on succeeding crops but systematic research to determine the non-N benefits from a range of legumes and over a range of soils and climates is sorely lacking. Such research efforts will require agronomists, soil scientists, plant pathologists, entomologists, and plant breeders to work together in a more multidisciplinary fashion than in the past. Broadening the knowledge base regarding non-N benefits is essential for promoting legumes in rice- and/or wheat-based cropping systems as a sustainable agricultural practice to regenerate depleted soil resources and arrest declining yields of the major cereals.

The soil environment in rice-rice or rice-wheat cropping systems is much different (in terms of N, phosphorus (P), soil moisture, soil compaction, soil organic matter, and soil biota) than in annual rainfed cropping systems where legumes are traditionally grown. Legumes may be affected by soil-borne diseases in the rice-wheat or rice-rice cropping systems that may be unimportant otherwise. For example, roots and nodules of chickpea were reported to be severely affected by black root rot (caused by *Fusarium solani)* in rice-wheat system fields in Bangladesh, Nepal, and Punjab State of India. Therefore, any program aiming to increase the area under legumes in general, and chickpea in particular should consider such little recognized adverse factors that may already be affecting yield and stability of these legumes. Diagnostic studies confirming suitability or otherwise of the soil environment for legumes in areas continuously growing rice-wheat or rice-rice will be required. Also, specific breeding programs targeting particular constraints faced by legumes in rice-wheat cropping systems of the IGP are needed. There is a particular need to devise ways of obtaining a high harvest index of legumes grown in high input systems; currently used cultivars manifest excessive vegetative growth which attracts biotic and abiotic constraints that depress grain yield.

Development of simulation models would allow identification of legume characteristics that are needed to optimize resource utilization in the rice-wheat cropping systems (RWCS). Successful simulation of crop growth and N_2-fixation would permit better conceptualization of constraints and opportunities for growing legumes in RWCS. More multilocational testing of agronomic packages of legumes with critical observations should be done as soil conditions for the rice-wheat systems can vary considerably from location to location, despite the commanality of the alluvial parent material. These tests would allow validation of models and permit generalizations that may be useful for other locations with different environmental conditions.

There is a need to study the mineralization of different legume residues and how that matches 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 vis-a-vis the soil type and the environment. 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 exist about the long-term effects of legumes on pests and diseases affecting the productivity of the rice and wheat system; and 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 RWCS in the IGP. Integrating the numerous and complex roles of legumes in soil fertility and crop growth might be assisted by simulation models. Cropping systems modeling capabilities have recently evolved and these tools should be used to explore various long-term options of including legumes in rice-wheat systems for farmers of this region.

Despite these gaps in our knowledge, legumes have generally been found to be beneficial in RWCS. However, farmers are yet to be convinced that they should include legumes in RWCS probably because of uncertain returns and high risks of legumes compared to the two cereals. There is not only a need to identify grain legumes that give high yields (>2 t ha^{-1}) in these systems but also that their stability of yield is better assured. Policy changes relating to assurance of inputs and market prices would also be required to encourage legume cultivation in rice-wheat systems for ultimately improving the sustainability of the system.

In the workshop, prospects for the different categories of legumes (winter, summer, and rainy season grain legumes, green manures, and forages) were discussed and compared. Although green manures offer large residual benefits to both rice and wheat, at least in terms of fixed-N_2 and organic matter conditions, farmers are reluctant to adopt these for sustainability of cropping systems. This is primarily because of labor requirements and costs for cultivation, lack of suitable equipment for incorporation into soil and, importantly, lack of any immediate monetary return from the green manure crop. A prime consideration therefore is to better marry the green manure role with an immediate monetary return through grain or forage for example. Increasing development of dairying and other livestock industries in the IGP is driving a need for more high quality forage, such as legumes can provide. Thus tranditional and exotic green manure or forage legumes need to be examined for their possible dual purpose potential (quality forage as well as large positive residual effects on the soil despite removal of above-ground forage material). Similarly, dual purpose green manure grain legumes need to be identified, with high biomass production for residue purposes and attractive grain yields. Short-duration pigeonpea approaches these criteria due to its prolific growth in the summer and rainy seasons in the IGP and at least promise of attractive yields (although instability of yield remains a problem).

Despite general recognition of lack of long-term sustainability of continuous cereal systems, it remains very difficult to convince a farmer to replace a rice or wheat crop with a legume. Therefore, the first priority should be to make maximum use of the small window in the rice-wheat rotation, during the summer period. There should be intensified efforts at genetic and agronomic improvement to fit grain legumes, such as mung bean, black gram, cowpea, and photoperiod insensitive extra-short-duration pigeonpea, between the wheat and rice crop. Despite their short growth duration, and resultant limited biomass production, results reported in this volume indicate that they can have substantial beneficial residual effects on rice certainly and wheat also.

To replace rainy season rice, where an option for rice remains, would require a rainy season legume tolerant of excess soil moisture conditions. Pigeonpea is particularly sensitive to waterlogging but soybean is less so. It is suggested that greater use could be made of soybean as a rainy season crop in the IGP. It is also difficult for winter legumes to compete with the assured high yields of wheat, where the option to grow wheat exists. But there are niches in the landscape where conditions are marginal, or even risky, for rice or wheat. For example, where tubewell water is relied upon for irrigation in an area where the water table is declining the high and stable yields of rice or wheat can no longer be assured. Thus even in traditionally irrigated areas it is possible to identify niches where the odds tilt towards legume cultivation. These niches need to be identified in a systematic manner and optimum technologies for legume production proposed, tested, and demonstrated on-farm. We would therefore look forward to more of a mosaic of cropping patterns in traditional rice and wheat production areas, with substantial areas of legumes. If this indeed occurs, the sustainability of the regional cropping systems should increase and rice and wheat yields in the fields where they are grown should resume an upward trend.

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About the Book

Among various agricultural production systems, the rice- and wheat-based cropping systems in the Indo-Gangetic Plain, covering Bangladesh, India, Nepal and Pakistan, are both agroecologically and socioeconomically important. There have been expressions of concern for long-term sustainability of rice- and wheat-based systems, as for other repetitive cropping systems. A closer examination of cropping sequences is needed if productivity of rice and wheat is to be maintained and further increased. In this context, the well-known ameliorative effects of legumes in crop rotations need close attention in relation to the sustainability of rice and wheat production systems.

This book is a product of a regional workship entitled "Residual effects of legumes in rice and wheat cropping systems of the Indo-Gangetic Plain" held at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India during 26–28 Aug. 1996. The objectives of the workshop were: (1) to collate and interpret existing infromation on legume residual effects on subsequent crops for the region and (2) to formulate future research needs. About forty participants representing Rice-Wheat Consortium member countries (Bangladesh, India, Nepal and Pakistan), Cornell University (USA), Vietnam, and ICRISAT participated in the workshop. The group discussed existing information on legume residual effects on subsequent crops for the region and then deliberated on research needs on grain legumes, forage legumes and green manure legumes in relation to constraints to adoption of technologies for including legumes, knowledge gaps and researchable issues, target regions and important cropping systems. This book is based on the papers presented and the deliberations of the workshop.

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