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Legumes in sustainable cropping systems

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Abstract

The beneficial aspects of legumes in sustainable cropping systems have long been known and extensively documented. Although grain legumes generally contribute less fixed N than pasture legumes, due to removal from the field of grain and stover of grain legumes, there is increasing evidence of their positive contribution to N balances and increased yields of succeeding crops. However, meaningful contributions of fixed N by legumes to the cropping system require intervention to ensure a vigorous legume-*Rhizobium* symbiosis. Recent studies suggest that up to half of the N fixed by grain legumes may remain below ground, and is thus potentially available for subsequent crops. Furthermore, there is increasing evidence of substantial non-N beneficial effects of legumes in cropping systems, such as breaking of pest, disease and weed cycles, increasing availability of mineral nutrients (other than N), improvements of soil physical characteristics, and soil health in general. Rationale for increased use of legumes in cropping systems also comes from rising costs of fossil fuels, and hence of N fertilizer, and increasing realization of the positive role of legumes in human nutrition and health. However, some negative effects of frequent use of legumes in cropping systems have also recently become apparent, such as soil acidification, build-up of pathogens affecting legumes as well as other crop species, soil water depletion and exposure of farmers to the financial risks associated with legume production. Nevertheless, despite the well documented overall net biophysical benefits of cultivating legumes, there

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has been stagnation in area sown and production of the major grain legumes, apart from lentil and cowpea, at the global level over the last decade. This can be attributed to various socio-economic factors, the principle one being the on-going risks associated with grain legume cultivation. Major risks result from the relative susceptibility of grain legume crops to several biotic stresses, unstable yields and fluctuating markets. There are some cropping systems with particular need and scope for infusion of grain legume cultivation. One such example is the rice-wheat systems of South Asia which face sustainability threats. Incorporation of crops like pigeonpea to substitute rice, chickpea and lentil to substitute wheat and mung bean between wheat and rice crops have been demonstrated to improve sustainability of rice-wheat systems. To increase the proportion of legumes in cropping systems world wide there is a need for focused research and development efforts, particularly to address the bottleneck biotic constraints, factoring in of overall economic benefits of legumes in cropping systems and better use of market information. Modeling tools are increasingly being used to assess the advantages and risks of incorporating legumes in cropping systems, and simple decision support systems to assist farmers in their choice of legumes in the cropping programs.

Introduction

The beneficial role of legumes in crop rotations has been lauded for millennia (White 1970; Karlen *et al.* 1994) but we seem to be no closer to optimizing legume benefits in cropping systems, to enhance the productivity, quality of produce and sustainability of those systems. Among the IFLRC focus legumes, only cowpea and lentil have registered noticeable increases in area over the previous 15 years (Fig. 1). Soybean and groundnut, although grain legumes but generally classified as oilseeds, have also increased in area since 1990 (Fig. 1), but the beneficial "legume effects" of these crops are relatively low. Modern soybean cultivars only fix reasonable quantities of nitrogen (N) if they are inoculated with specific rhizobia (Date 2000); mostly, soybean crops are fertilized with mineral N fertilizer in the manner of non-legumes. Groundnut also fixes limited quantities of N and little crop residue is left from the groundnut crop as plants are uprooted and removed from the field at harvest (Nambiar 1990). Values for grain legume production show similar trends as in Fig. 1 because yield increases for all depicted legumes since 1990 have been within the range 0-1% per annum. The data of Fig. 1 suggest that grain legumes in general are not increasingly contributing to cropping system sustainability, despite their well-documented potential for doing so.

Currently, there is increased urgency to promote the role of legumes in cropping systems, generated by the rapidly rising cost of fossil fuels with little prospect of this trend reversing. Nitrogenous fertilizer price is closely related to the price of fossil fuels so the value of N fixation to global agriculture will further increase. Nitrogen fixation benefits are not captured if legume nodulation is sub-optimal, legume growth is not vigorous and use of legumes in cropping systems is not widespread.

Initial concerns about cropping system sustainability were primarily directed to biophysical factors. A sustainable cropping system was considered to be one in which

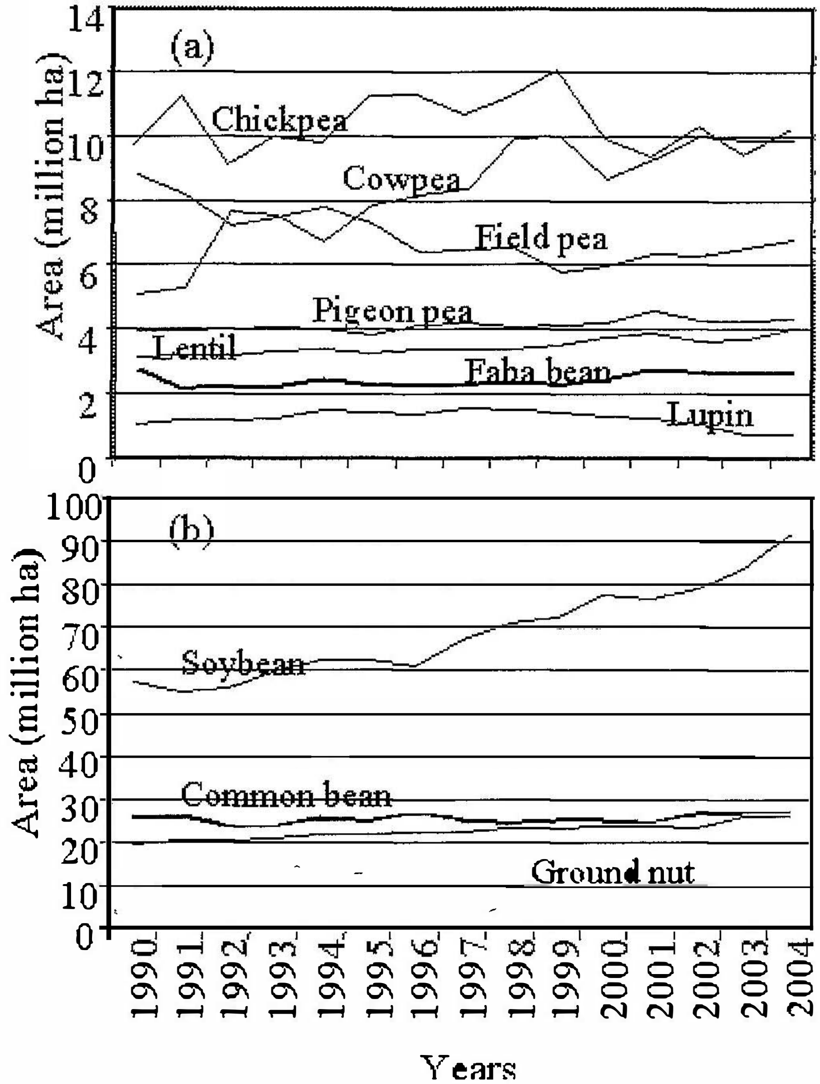

Fig. 1. Changes in global area sown to the major grain legumes from 1990 to 2004. Beans refers to *Phaseolus* and *Vigna* species, except cowpea (*Vigna unguiculata*). Source: FAO (2005)

production was maintained or increased without damaging, and perhaps even enhancing, the resource base. Legumes were considered to have a major role to play in rendering cropping systems sustainable, primarily due their additions of fixed N, but also due to other beneficial legume effects such as breaking of pest and disease cycles for non-legume crops. However, as concepts of cropping system sustainability evolved a greater socio-economic perspective has developed. Not only must production be maintained or increased without damaging the resource base but also the livelihoods of those dependent on cropping, and the community at large, need to be unequivocally improved as a result of the changed cropping system. If biophysical deterioration of farming systems is to be adequately addressed, then key socio-economic aspects need to be accounted for. This particularly applies to diversifying the cropping system by increasing legume components, due to the risky nature of legume cultivation in comparison with that of staple cereal crops, for example.

There have been several recent reviews examining the role of grain legumes in cropping system sustainability (e.g. Karlen *et al.*, 1994; Peoples *et al.*, 1995; Kumar Rao *et al.*, 1998; Howieson *et al.*, 2000; Johansen *et al.*, 2000; Pala *et al.*, 2000; Conner 2001; Evans *et al.*, 2001; Gowda *et al.*, 2001), discussing the beneficial effects of legumes but also alluding to some of the constraints to greater use of legumes in cropping systems to improve their sustainability. The purpose of this review is to update on recent knowledge in this area. Advances in our understanding over the previous decade of both beneficial and detrimental biophysical effects of food legume cultivation will be evaluated. In particular, the socio-economic factors constraining expansion of cultivation of grain legumes will be examined. Aspects relating to human nutrition and health will also be discussed. Suggestions will be given for increasing the use of food legumes such that they may more substantially contribute to cropping systems sustainability and thereby to human well-being. Some recent examples of inclusion of legumes in cropping systems will be given.

Beneficial Effects of Legumes

Overall Cropping System Productivity

The major beneficial effect of including legumes in cropping systems is considered to be their residual effects on following, usually non-leguminous, crops. Of the residual effects, additions of fixed N are assumed to be most important but, as discussed below, there are several other positive benefits. However, there are benefits of including grain legumes in cropping systems additional to residual effects. One such benefit is, simply, increasing cropping intensity and thus the annual productivity of the cropping system. An example is the cultivation of chickpea after rice in traditional rainfed systems having only one crop of rice per year (Musa *et al.*, 2001). Addition of legumes to existing cropping systems increases the diversity of such systems. This can reduce risk, by reducing reliance on one or few crops in a year, even though legumes themselves may be risky crops. To increase cropping intensity, however, it is often necessary to adjust the growing period of existing crops. This is the case for post-rice rainfed crops where the traditional rice varieties are of the longest duration possible to make best use of available soil moisture and other environmental factors. Introduction of a shorter duration rice variety, without a reduction in its yield potential, can increase the possibility of being able to sow post-rice crops under optimum soil moisture and temperature conditions and thus maximize their yield. One such example is the introduction of shorter duration rice varieties in the High Barind Tract of Bangladesh which allows more timely sowing of chickpea (Witcombe *et al.*, 2005).

Overall beneficial effects of legumes can be measured by growing a non-legume after a legume crop, or range of legumes, and the non-legume with which legumes are to be compared. Table 1 gives some examples of overall legume beneficial effects, but without the information to ascertain the extent to which extent fixed N is contributing to the yield increase; the data show the total residual effect of the legumes whatever its mechanism. Beneficial effects of growing grain legumes on subsequently sown non-legumes can be several-fold, but are usually not as high as with a green manure crop due to return of most of the plant biomass to the soil in the case of the green manure crop (Table 1). However, extent of legume benefit can vary enormously, depending on the location, soil type, sowing date, weather, stress factors affecting the various crops, etc. (e.g. Walton and Trent, 1988; Evans *et al.*, 2003).

Table 1. Some examples of beneficial effects of growing legumes on subsequent cereal crops

Reference	Location	Crops compared	Following non-legume	Grain yield of following crop	Beneficial legume effect
				g ha^{-1}	%
Marcellos (1984)	Tamworth, New South Wales, Australia	Faba bean (Fiord)	Wheat	2.93	186
		Lupin (Illyarrie)		3.20	204
		Lupin (Ultra)		3.14	200
		Chickpea (CPI56288)		3.19	203
		Chickpea (CPI61277)		2.97	189
		Wheat (Kite)		1.57	
Walton & Trent (1988)	Gibson, Western Australia	Faba bean	Wheat (var. Egret)	1.19	372
		Field pea		1.46	456
		Grasspea		1.02	319
		Lupin		1.50	469
		Wheat		0.32	
Evans *et al.* (2003)	Wagga Wagga, New South Wales, Australia	Pea	Wheat	3.50*	233
		Lupin		3.90	269
		Clover green manure		5.80	387
		Wheat		1.50	
Shah *et al.* (2003)	NWFP, Pakistan	Mungbean	Wheat	1.030	136
		Sorghum		0.760	
		Lentil	Maize/sorghum	5.70	150
		Wheat		3.80	

*Yield estimated from Figure 2 of Evans *et al.* (2003)

The traditional way of interpreting crop response when multiple factors are involved is through the "law of limiting factors", whereby yield is responsive to only one, most limiting, factor (Kho, 2000). However, this paradigm has proved inadequate, due to such phenomena as sequential influence of factors at different time scales, different factors affecting different components of the system and pseudo-substitution of inputs (Sadras *et al.*, 2004). An alternative paradigm is co-limitation, where the response of a biological system to two or more factors is greater than its response to each factor in isolation (Sadras *et al.*, 2004). In interpreting the effects of prior crops of faba bean, and of pastures, on wheat yield, Sadras *et al.* (2004) showed that water and N stress acted in a manner consistent with co-limitation. The APSIM (Agricultural Production Systems Simulator) model was used to calculate the individual and overall effects of the major stresses of water and N. It is suggested that this methodology is appropriate for unraveling reasons behind overall residual benefits of legumes on following crops.

Additions of Fixed Nitrogen

The predominant mechanism by which legumes favour growth and yield of a subsequent crop is by increasing availability of N to the subsequent crop. This can be through additions of fixed atmospheric N to the soil N pool or by a N sparing effect, whereby the legume largely relies on its own N fixation for its N requirements thereby not depleting soil N and leaving this N available for the subsequent crop. Peoples *et al.* (1995) summarized data to a decade ago on the proportion and amount of N in legumes that is fixed (Table 2). More specific crop x location data for these parameters are given in Table 3. More recent literature confirms the values reported in Tables 2 and 3 (e.g., Unkovich and Pate, 2000). There is a wide range values for N fixed but it can be generalized that the optimal rate of N fixation in grain legumes is perhaps about 1 kg N ha^{-1} day^{-1} within a cropping season, and this should be considered as the potential of the grain legumes for N fixation within a given environment. From surveys of N fixed by legumes in eastern Australia, Peoples *et al.* (2001) concluded that 20-25 kg of shoot N was fixed for every tonne of legume shoot dry matter produced. This value was of the order found in other such studies done elsewhere in the world. Deviations from these values were attributable to drought stress or elevated soil nitrate levels which suppressed N fixation. The wide variations in N fixation within a given crop are found for a variety of reasons but basically depend on the amount of biomass produced by the legume and the effectiveness of the legume-*Rhizobium* symbiosis in fixing N. A range of biotic and abiotic factors determine each of biomass production and symbiotic effectiveness. There is a clear relationship between the N fixed by grain legumes and the N balance (Fig. 2).

Table 2. Range of estimated proportion (P_{fix}) and amount of N fixed by major grain legumes, as reported by Peoples *et al.* (1995)

Grain legume	P_{fix} %	Amount N fixed kg N ha^{-1}
Cool season legumes		
Chickpea (*Cicer arietinum*)	8-82	3-141
Lentil (*Lens culinaris*)	39-87	10-192
Pea (*Pisum sativum*)	23-73	17-244
Fababean (*Vicea faba*)	64-92	53-330
Lupin (*Lupinus angustfolius*)	29-97	32-288
Warm season legumes		
Soybean (*Glycine max*)	0-95	0-450
Groundnut (*Arachis hypogaea*)	22-92	37-206
Common bean (*Phaseolus vulgaris*)	0-73	0-125
Pigeonpea (*Cajanus cajan*)	10-81	7-235
Mungbean (*Vigna radiata*)	15-63	9-112
Blackgram (*Vigna mungo*)	37-98	21-140
Cowpea (*Vigna unguiculata*)	32-89	9-201

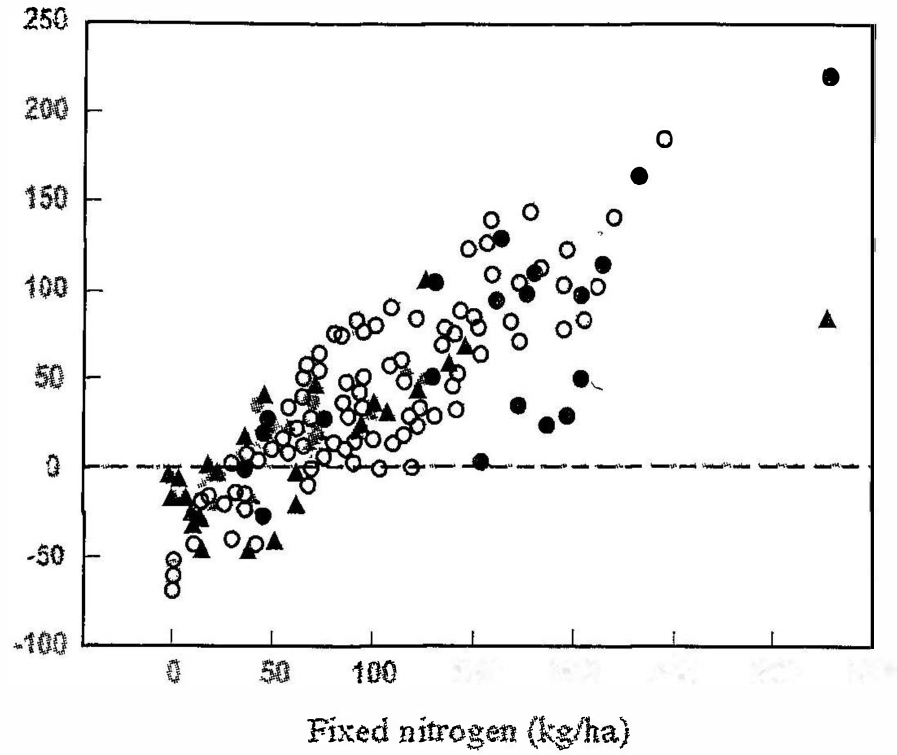

Fig. 2. Effect of fixed N on the N balance of pea (O), lupin (●) and chickpea (◆) grown in Australia. Source: Evans *et al.* (2001)

For grain legumes to play an important role in the maintenance of soil fertility for other crops in the rotation, they must leave behind more N from N fixation than the amount of soil N that is removed by the crop. The amounts of N added to the cropping system that have been measured are quite variable for different species (Table 4). There can also be large varietal differences in residual N, as found for a range of six lupin varieties (63-177 kg/ha; Hamblin *et al.*, 1993). In a survey of farmers' fields in north-west New South Wales, Australia, Schwenke *et al.* (1998) found that chickpea needs a P_{fix} of >35% and faba bean a P_{fix} of >19% to balance soil N. The largest net additions of fixed N tend to be found with crops or varieties that have a smaller N harvest index, e.g. long-duration pigeonpea in India or cowpea in Ghana. Grain legumes can contribute large amounts of N to the soil in fallen leaves and stover that can provide N for subsequent crops. If the legume stover is removed from the field, however, there is often no observable benefit to the next crop and there is usually a net removal of N from the cropping system in the legume grain. Increases in the amount of legume N contributed through residual effects are generally possible only if the grain yield of the legume is decreased. This can rarely be justified in economic terms (Schwenke *et al.*, 1998) but might be worthwhile for marginal farmers in remote areas who are unable to participate in a cash economy.

Information on the residual effect of various summer, rainy season, cool season, green manure and forage legumes on succeeding cereal crops in South Asia is available (Kumar Rao *et al.*, 1998). Increase in cereal yields following monocropped legumes was reported to range 0.5-3 t ha^{-1} representing a 30-350% increase over yields in cereal-cereal cropping sequences (Peoples and Crasswell, 1992). In a long-term trial involving legume and non-legume based systems, conducted at ICRISAT Center, Patancheru, Hyderabad, India, since

Table 3. Some estimates of N_2-fixation by important pulses and legume oilseeds grown as sole crops

Legume	N_2 fixed		Country	Method†	Reference
	kg N ha^{-1}	%			
Groundnut	139-206	55-64	Australia	NA	Peoples *et al.* (1991)
	68-116	54-78	Brazil	ID	Boddey *et al.* (1990)
	152-189	61-85	India	NA	Nambiar *et al.* (1986)
	46‡	62	Thailand	ID	Toomsan *et al.* (2000)
Pigeonpea	68-88	88	India	ID	Kumar Rao *et al.* (1987)
	0-76	0-36	India	NA	Kumar Rao *et al.* (1996)
	1-39	64-100	Zimbabwe	NA	Mapfumo *et al.* (1999)
Chickpea	61-126	81-88	Bangladesh	ID	Sattar *et al.* (1998)
	4-61	23-68	Pakistan	ID	Hafeez *et al.* (1998)
	67-85	63-81	Australia	NA	Herridge *et al.* (1995)
	20-42	42-87	India	ID	Rupela and Saxena (1987)
Soybean	15-170	12-100	Nepal	NA	Maskey *et al.* (1997)
	42-83	46-87	Nigeria	ID	Sanginga *et al.* (1997)
	149-176	69-74	Philippines	ID	George *et al.* (1995)
	108-152‡	66-68	Thailand	ID	Toomsan *et al.* (1995)
Grasspea	85-91‡	—	Nepal	NA	Maskey *et al.* (1997)
Lentil	19-83‡	62-85	Nepal	NA	Maskey *et al.* (1997)
Lupin	95-283	74-93	Australia	NA	Unkovich *et al.* (1995)
Pea	54-165	60-91	Australia	NA	Unkovich *et al.* (1995)
	39-94‡	36-65	Canada	DB	Soon and Arshad (2004)
Common bean	4-45	12-53	Brazil	ID	Hardarson *et al.* (1993)
	8-26‡	40-51	Tanzania	ID	Giller *et al.* (1998)
Greengram	0-55	0-100	Pakistan	NA	Shah *et al.* (1997)
	10‡	25	Thailand	ID	Toomsan *et al.* (2000)
Blackgram	0-55	0-100	Pakistan	NA	Shah *et al.* (1997)
	9-51	32-74	Brazil	ID	Boddey *et al.* (1990)
	63‡	65	Thailand	ID	Toomsan *et al.* (1995)

† NA = ^{15}N natural abundance; ID = ^{15}N isotope dilution; DB = difference or N balance method; ‡ Measurements made in on-farm crops.

1983, rainy season sorghum grain yield production was sustained at about 2.7 t ha^{-1} over 12 years within a continuous sorghum-pigeonpea intercrop system compared to about 1.3 t ha^{-1} in a non-legume based system (Rego and Rao, 2000). With a cowpea-pigeonpea intercrop system, succeeding sorghum benefited each year by about 40 kg N ha^{-1} (fertilizer N equivalent). In the same study legume benefits were less marked in the chickpea-based rotation than in the pigeonpea system - a 12-year build-up of soil total N (about 125 μg g^{-1}) was observed in the pigeonpea system. Although sorghum benefited from this system,

Table 4. Net N-balance for grain legumes following seed harvest

Legume	Location	Seed N† kg N ha⁻¹	Total crop kg N ha⁻¹	NHI§	N_2 fixed¶ P_{fix} %	N_2 fixed¶ Amount kg N ha⁻¹	Net N balance#	Reference
Groundnut	Thailand	116	245	0.41	61	150	+34	Suwanarit *et al.* (1986)
Pigeonpea	India E††	39	72	0.54	10	7	-32	Kumar Rao and Dart (1987)
	India M††	49	120	0.41	46	55	+6	
	India L††	28	134	0.21	51	69	+41	
Cowpea	Australia	80	125	0.64	69	87	+7	Ofori *et al.* (1987)
	Ghana	65	226	0.29	89	201	+136	Dakora *et al.* (1987)
Lentil - residue	Pakistan	39	-	-	73	68	+16	Shah *et al.* (2003)
Lentil + residue		40	-	-	73	68	+27	
Mungbean - residue		40	-	-	70	74	+9	
Mungbean + residue		48	-	-	79	112	+64	
Mungbean	Australia	89	177	0.50	63	112	+23	Chapman and Myers (1987)
Fieldpea	Australia	28	199	0.14	75	142	+114	McNeill *et al.* (2000)
Chickpea		31	120	0.26	74	85	+54	
Fababean		63	235	0.27	77	187	+124	
lupin		43	229	0.19	86	189	+146	
Albus lupin	Australia	266	317	0.84	75	317	-6‡‡	Armstrong *et al.* (1997)
Narrow leaf lupin		154	249	0.62	82	249	+10‡‡	
Fieldpea		148	163	0.91	60	133	-80‡‡	
Chickpea		94	104	0.91	75	104	-62‡‡	

† N removed in seed, SN; ‡ Total N at maturity, TN; § Nitrogen harvest index = SN/TN; ¶ Quantity of N_2 fixed, Nf = TN x P (P=proportion); # Net contribution of legume residue N to soil = Nf-SN; †† E = early, M = medium, L = late duration pigeonpea; ‡‡Net N balance after harvest of a subsequent wheat crop and including an estimate of below-ground N derived from the legume.

pigeonpea yields declined over time due to soil-borne fungi and nematodes. Wider rotations of crops with pigeonpea may help to overcome these problems, while sustaining sorghum production.

The fertilizer N equivalent of the residual effect of different grain legumes on maize was reported to range from 7 kg ha^{-1} to 70 kg ha^{-1}, on rice 12-67 kg ha^{-1}, on wheat 23-78 kg ha^{-1}, on sorghum 40-68 kg ha^{-1}, and on pearl millet 40 kg ha^{-1} (Table 5). The green manure and forage legumes were reported to have fertilizer N equivalents of the residual effect on rice ranging between 50 and 100 kg ha^{-1}. The residual effect of grain legumes as expressed in fertilizer N equivalent was less in intercropping compared to sole crops, due to the lower plant density of grain legumes in intercrops. 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 biological nitrogen fixation and the "N sparing effect" which results from substitution by legumes of biologically fixed N for soil N. Therefore, FRV methodology over-estimates 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 overestimation by FRV methodology is because it confounds the non-N rotation effect with the N contribution (through BNF or N sparing effect).

The FVR methodology also assumes that use-efficiency of fertilizer and legume N is similar. In some situations the following cereal crops can better access N in legume residues than equivalent amounts of fertilizer N added to the soil surface. Armstrong *et al.* (1997) found that N uptake by sorghum was greater from plots where mung bean had grown previously rather than N fertilized plots, even though similar quantities of N were involved. This was because the legume-derived N was deeper in the soil while fertilizer N was in the soil surface, which rapidly dried out causing N from that soil layer to become unavailable.

Recent studies using shoot or stem labeling with ^{15}N have shown that the below-ground N contribution of legumes is much greater than previously thought (McNeill *et al.*, 1997). In the glasshouse experiments, below-ground N represented 30% of total N in faba bean and 48% in chickpea. Under field conditions these figures were 26% and 68% for faba bean and chickpea, respectively (Khan *et al.*, 2000). In pot studies, where the entire plant biomass can be recovered, the shoot:root N ratio was in the range 1.4-2.2 for chickpea, lupin, faba bean, vetch and lentil (Unkovich and Pate, 2000). In field studies, below-ground N was estimated to be in the range 38-50% for field pea, chickpea, faba bean and lupin (McNeill *et al.*, 2000). In a series of field and glasshouse studies, Peoples (2001) estimated below ground N in faba bean, chickpea, lentil and soybean to be in the range 26-68%. In view of these apparently high values, it appears that the value of legumes in contributing N to subsequent crops will need to be re-assessed.

Growing legumes in rotation improves 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; Rego and Rao, 2000) (Table 6). However, it does not fully explain the beneficial

Table 5. Residual effect of legumes grown as sole and intercrop with a cereal on a following cereal yield in terms of fertilizer-N equivalents

Preceding legume	Following cereal	Fertilizer-N equivalent kg ha [1]
Pigeonpea (sole)	Maize	40
Pigeonpea/sorghum	Maize	20+
Groundnut	Wheat	28
Groundnut/maize	Wheat	12
Mungbean	Wheat	68
Mungbean/maize	Wheat	16
Cowpea	Wheat	38
Cowpea/maize	Wheat	13
Cowpea/pigeonpea	Sorghum	40
Blackgram	Sorghum	68
Soybean	Maize	7
Chickpea	Pearl millet	40
Chickpea	Maize	60-70
Chickpea	Wheat	40
Lentil	Maize	18-30
Lentil	Pearl millet	40
Peas	Maize	20-32
Peas	Pearl millet	40
Peas	Wheat/flax	12-28
Berseem	Maize	123
Sweet clover	Maize	83
Grasspea	Maize	36-48
Cowpea	Rice	67
Mungbean	Rice	48
Blackgram	Rice	36
Guar	Rice	14
Common bean	Rice	12
Blackgram	Wheat	30
Cluster bean	Wheat	78
Blackgram	Wheat	65
Pigeonpea	Wheat	23
Soybean	Wheat	58
Groundnut	Wheat	49
Mungbean stover	Rice	80
Green manure legumes	Rice	50-100
Forage legumes	Rice	50-90

Source: Derived from Kumar Rao *et al.* (1983), Singh and Verma (1985), Bandyopadhyay and De (1986), Carberry (1995), Wani *et al.* (1995), Beckie and Brandt (1997), Ahlawat *et al.* (1998), Kumar Rao *et al.* (1998), Lauren *et al.* (1998), Saraf *et al.* (1998), Rego and Rao (2000).

effects of legumes on the following crop. Direct evidence of the benefits from N fixation was obtained where yields of sorghum grown after nodulating varieties of chickpea were higher than yields after non-nodulating varieties of chickpea (Kumar Rao and Rupela, 1998). The increased cereal yields following legume crops are usually attributed to the N contribution

Table 6. Some examples of the increased levels of soil nitrate detected following legume growth.

Crop species	Additional soil nitrate† kg N ha^{-1}	Reference
Chickpea	14	Herridge *et al.* (1995)
Chickpea	33	Marcellos *et al.* (1998)
Mungbean	26	Doughton and MacKenzie (1984)
Blackgram	38	Doughton and MacKenzie (1984)
Pigeonpea	15	Ladha *et al.* (1996)
Crotalaria	19	
Siratro	26	
Sorghum/pigeonpea	32‡	Rego and Rao (2000)
Cowpea/pigeonpea	30‡	
Fieldpea	46-54	Soon and Arshad (2004)
Common vetch	6	Walton and Trent (1988)
Fieldpea	7	
Narrow-leafed lupin	8	

†Calculated as the difference between the levels of soil nitrate after a legume and after a cereal crop or a period of fallow; ‡Includes mineral and mineralizable N

from legumes in crop rotation (De *et al.*, 1983; Kumar Rao *et al.*, 1983), while others think that factors besides the N contribution may be of equal or perhaps greater in importance in enhancing cereal yields after legumes (Danso and Papastylianou, 1992; Fyson and Oaks, 1990; Wani *et al.*, 1991a, 1994; Stevenson and van Kessel, 1996).

Intercropping of grain legumes with cereal crops is common in tropics. The crop combinations and sowing arrangements are very large and range from mixed cropping, in which many species are sown in a field, to an organized row or strip cropping (Francis, 1986). The combination of crops is determined by the length of growing season and environmental adaptation, but usually early- and late-maturing crops are combined to ensure efficient utilization of the resources during the growing season. In tropical regions the legumes such as cowpea, pigeonpea, groundnut and chickpea are usually intercropped with maize, sorghum, millet, safflower or rice. The quantity of N fixed by the legume in an intercrop depends on the species, plant morphology and legume density in the intercrop mixture and crop management practices (Table 7). Differences in the competitive abilities of the component crops for soil-N can result in stimulation of N fixation (Rerkasam *et al.*, 1988). However, N fixation by climbing types of common bean was unaffected by intercropping with maize (Graham and Rosas, 1978), whereas shading by tall cereal crops can reduce both yield and N fixation of shorter stature legumes such as groundnut (Nambiar *et al.*, 1983).

A dilemma arises when soil nitrate levels substantially increase after additions of fixed N through vigorous legume growth. As soil nitrate levels increase, N fixation capacity decreases, and chickpea is particularly sensitive in this regard (Doughton *et al.*, 1993;

Schwenke *et al.*, 1998; Turpin *et al.*, 2002). This relationship is so robust that Herridge *et al.* (1998) have been able to predict N fixation and N balance using soil nitrate at sowing and chickpea yield. To maximize contributions of fixed to the soil N balance, legume symbioses less sensitive to external nitrate concentration are required.

Table 7. Effect of intercropping grain legume with cereals on crop-N derived from N_2-fixation

Species	Location	Legume: cereal ratio	N_2-fixed		Reference
			P_{fix} %	Amount kg N ha^{-1}	
Rice bean	Thailand	100:0	36	49	Rerkasem *et al.* (1988)
		25:75	86	41	
Cowpea	Australia	100:0	69	87	Ofori *et al.* (1987)
		71:29	66	59	
	India	100:0	54	64	Patra *et al.* (1986)
		66:33	58	48	
	Hawaii	100:0	30	18	Van Kessel and Roskoski (1988)
		75:25	34	10	
	Nigeria	100:0	79	118	Eaglesham *et al.* (1981)
		62:38	59	72	
Pigeonpea	India	100:0	88	88	Kumar Rao *et al.* (1987)
		100:100	96	75	
	India	100:0	63	150	Tobita *et al.* (1994)
		100:100	86	165	
Pea	Denmark	100:0	53	128	Jensen (1996)
		46:54	82	31	

Effects on Soil Organic Matter

Legumes can play an important role in maintaining and improving levels of soil organic matter, which is essential for the physical, chemical and biological suitability of soil for agriculture, often now referred to as "soil health" (Johnston, 1991). Organic carbon (C) content has been shown to increase in legume-based cropping systems as compared to wheat-maize or fallow-maize cropping sequences (Table 8). Among the legumes, grasspea as a preceding crop proved superior to lentil, pea and chickpea, which in turn significantly increased the organic C in soil over fallow and wheat treatments (Table 8). An increase in organic C content in soil through legumes has also been reported by Rixon (1966), Russell (1977), George and Prasad (1989), Schulz *et al.* (1999), and Aslam *et al.* (2003).

A major consequence of build-up of soil organic matter is improvement of soil structure, which improves tillage characteristics and soil water holding capacity. Improvements in soil structure, mainly soil aggregate formation, where observed after after three years of alfalfa, clover and hairy vetch (*Vicia villosa*) mixture (Latif *et al.*, 1992; Karlen *et al.*, 1994). Improvements in soil water-holding and buffering capacity have been attributed to incorporation of legume residues (Buresh and De Datta, 1991). Improvements in soil structure

Table 8. 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†			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}
Grasspea	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

† OC = organic carbon, N = nitrogen; and P = phosphorus; Source: Ahlawat *et al.* (1977)

due to legume cultivation can also decrease soil erosivity (Bruce *et al.*, 1987). However, there are some reports where inclusion of a legume, e.g. mungbean in rice-wheat systems, resulted in decline in organic C content of soil (Meelu *et al.*, 1979; Ram Newaj and Yadav, 1994). The reasons for this decline in organic C content of soil are not clear – perhaps a result of excess tillage.

Soil organic matter levels in turn affect the level of soil microbial activity. Soil microbial biomass is known to be both a source and a sink for nutrients, that is, the soils with more biomass will be able to release nutrients more rapidly. In a rice-wheat system, inclusion of summer mungbean 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, indicating increased microbial activity. Increased microbial activity influences 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 cereal (e.g. rice-wheat)-based system improves soil microbial biomass and activity that could be vital for long-term soil health and productivity.

Significant enhancement of soil microbial populations through legume cultivation can also occur in cool temperate regions. In the Canadian Prairies, Biederbeck *et al.* (2005) showed that after 6 years of cultivating pea, lentil or *Lathyrus* spp. microbial activity had substantially increased compare to the traditional fallow treatment. On average across legumes, bacterial numbers had increased 385%, filamentous fungi 210%, microbial biomass C 170%, microbial biomass N 191%, cumulative C mineralization 205%, dehydrogenase 202%, phosphatase 171% and arylsulfatase activity 287%.

It is difficult to measure small changes in the total soil N pool or C pool on an annual basis as the soil pools are large and significant differences only become apparent over time.

Table 9. Effect of a summer legume, mungbean, on microbial biomass and population in soil at 0-15 cm depth, New Delhi, India, 1993-94†

Treatment‡	Microbial biomass		Microbial population					
	Wheat harvest	Rice harvest	Bacteria x 10^5	Actino-mycetes x 10^4	Fungi x 10^4	*Azoto-bacter* x 10^2	*Azospiri-llum*	PSB§ x 10^2
	μg g^{-1} soil		number g^{-1} soil					
Rice crop (1993)								
Fallow	185	219	55	0.5	0.2	25	1.2	-
Mungbean (SR)	198	225	115	1.5	1.0	92	18.7	4.0
Mungbean (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
Mungbean (SR)			42	38.0	0.6	35	0.250	2.5
Mungbean (SI)			65	140.0	0.9	65	0.750	4.2

†Statistical analysis of the data is not available; ‡SR = Stover removal; and SI = Stover incorporation; § PSB = Phosphate solubilizing bacteria; Source: Ahlawat *et al.* (1998)

Therefore, long term rotational studies are needed to determine whether grain legumes deplete or enrich soil N (Chalk, 1998) and soil organic matter (Christensen and Johnston, 1997) and the number of such studies is limited.

Wani *et al.* (2003) evaluated the impact of improved cropping systems involving legumes (and land and water management factors) versus a traditional farming practice (fallow-sorghum or chickpea) in central India on crop productivity and soil quality (Table 10). The average grain yield of the improved system over 24 years was 4.7 t ha^{-1}, nearly a five-fold increase over the traditional system (about 1 t ha^{-1} yr^{-1}). There was also evidence of increased organic C, total N and P, available N, P and K, microbial biomass C and N in the soil of the improved system. A positive relationship between soil available P and soil organic C suggested that application of P to vertisols increased carbon sequestration by 7.4 t C ha^{-1} and, in turn, the productivity of the legume-based system, thus ultimately enhancing soil quality.

Campbell *et al.* (2000) evaluated the impact of cropping systems on total soil N and C and the effect on net N mineralization over the period from 1976 to 1990. They reported that wheat-lentil rotations increased total soil N from 3.26 to 3.58 t ha^{-1}, whereas total soil C for fertilized wheat increased from 34.7 to 36.6 t ha^{-1} for the wheat-lentil rotation (Table 10). Furthermore, net N mineralization increased significantly in the wheat-lentil rotation. Although this rotation received 13 kg N ha^{-1} less fertilizer per year than the continuous wheat treatment, lentil increased the total soil N pool at an annual rate of 23 kg N ha^{-1} compared to 8 kg N ha^{-1} for the fertilized wheat.

Table 10. Changes in soil N, C and P with inclusion of grain legumes in various cropping systems

Crop rotation†	Study period‡	Fertilizer N input kg N ha^{-1} $year^{-1}$	Total N kg N ha^{-1}	N mineralization kg N ha^{-1}	Total C t C ha^{-1}	Olsen P kg P ha^{-1}
From Wani *et al.* (2003)						
F – SG or CP	1976-1998	10 t ha^{-1} farmyard manure in alternate years	2,276	32.6	21.4	1.5
SG/PP or MA - CP		60 kg N + 20 kg P ha^{-1}	2,684	-3.3	27.4	6.1
From Rego and Seeling (1996); Wani *et al.* (1996); and Rego and Rao (2000)						
SG/SF, SG+SF	1983-1994/ 1999§	0	508¶	6#	0.365††	ND‡‡
S+CP, S+SF		0	550	11	0.371	ND
SG/PP, SG+SF		0	610	12	0.419	ND
CO/PP, SG+SF		0	638	19	0.435	ND
From Campbell *et al.* 2000; and Campbell and Zentner (1993)						
WH	1976-1990	31	3,370§§	17¶¶	34.68##	ND
WH - LE		18	3,580	34	36.56	ND

† F = fallow SG = sorghum; CP = chickpea; PP = pigeonpea; MA = maize; SF = safflower; SB = soybean; CO = cowpea; WH = wheat; LE = lentil; ‡ Year of initiation and final sampling of the study; § N measured in 1994 and C in 1999.; ¶ Units are mg N kg^{-1} soil and the initial value in 1983 was 550 mg N kg^{-1} soil; # Units are mg N kg^{-1} soil.; †† Organic carbon (%) in 0-15 cm soil depth (T.J.Rego, personal communication); ‡‡ Not determined; §§ kg N ha^{-1} in 0-15 cm soil profile and the initial value in 1976 was 3,260 kg N ha^{-1}; ¶¶ kg N ha^{-1} in 0-90 cm soil profile; ## Initial value in 1976 was 30.47 t C ha^{-1}.

Another long-term study examined cowpea, pigeonpea and chickpea grown in rotation with sorghum and safflower from 1983 to 1994 (Table 10) (Rego and Seeling, 1996; Rego and Rao, 2000; Wani *et al*., 1996). Unfertilized cowpea plus pigeonpea and sorghum/ pigeonpea rotations increased total soil N content after 10 years (Table 10). Conversely, a slight decline in total soil N occurred in rotations of sorghum and chickpea or when grain legumes were not included. Furthermore, N uptake by sorghum increased when grain legumes were part of the rotation as the N supplying power of the soil increased when grain legumes were included. Although the grain and the above-ground residues were removed, the below-ground N contribution was large enough to increase the total soil N content and enhance net N mineralization. Similarly, the organic C (%) of the soil (0-15 cm) also increased in treatments having legumes (Table 10).

From the above reports it is clear that grain legumes can increase total soil N and also soil C thus contributing to soil health and sustainable productivity. The value of grain legumes in cropping systems is predicated on the ability of the grain legumes to fix the majority of its N and to leave substantial residues of C and N in the soil.

Availability of Other Nutrients

Recent studies have indicated an important role of legumes in increasing availability of P in cropping systems. One mechanism of achieving this is uptake of P by legume roots from parts of the soil profile not normally accessed by non-legumes. This can be through more thorough exploitation of a given soil volume, as occurs with mycorrhizal development (Harrier and Watson, 2003) or formation of proteoid roots (Gardner *et al.*, 1981). It can also be through deeper rooting of legumes than cereals in the rotation and thus recycling of P and other nutrients to the soil surface to be available for uptake by subsequent crops. However, these effects are difficult to quantify.

Another mechanism is the mobilization of sparingly soluble P by legume root exudates; e.g. citric and malic acids and malonate in chickpea (Ae *et al.*, 1991; Wouterlood *et al.*, 2004), citric and malic acid in lupin (Gerke *et al.*, 1994), and piscidic acid in pigeonpea (Ae *et al.*, 1990). These exudates can act directly in solubilizing calcium, iron or aluminium phosphates or indirectly by stimulating growth of phosphate solubilizing bacteria (Gull *et al.*, 2004). Pot studies have clearly shown that growth of a legume which exudes low molecular weight organic compounds from roots results in increased growth and P uptake of a cereal grown subsequently in the same pot; e.g. in maize following chickpea (Arihara *et al.*, 1991), in wheat following either faba bean, field pea or white lupin ((Nuruzzaman *et al.*, 2005), and in sorghum and wheat following white lupin (Hocking and Randall, 2001). When chickpea was grown as an intercrop with wheat in pots, P uptake by wheat was enhanced, as compared with a sole wheat crop (Li *et al.*, 2003a). Some recent field studies have now demonstrated enhancement of growth and P uptake by subsequent cereal crops. Amrani *et al.* (2001) showed that residual P effects on wheat where greater in chickpea-wheat rotations than in wheat-wheat rotations. Horst *et al.* (2001) demonstrated a positive rotational effect of P-efficient leguminous crops on subsequent cereal crops. Faba bean enhanced P uptake of maize in the field when it was intercropped with maize (Li *et al.*, 2003b).

It is proposed that legumes can also increase availability of nutrients additional to N and P, namely K, Ca, Mg, Zn, S and Fe, through increased soil microbial activity, deep rooting, and root exudates (Kucey *et al.*, 1988; Ladha *et al.*, 1989 and Wani *et al.*, 1991b). Growth promoting substances have also been reported to emanate from legume residues (Fyson and Oaks, 1990; Ries *et al.*, 1977).

Effects on Biotic Stresses of the Cropping System

It has long been reported that crop rotations, including those with legumes, are important in breaking pest and disease cycles of particular crops (Karlen *et al.*, 1994). Recent studies have quantified further instances of this effect, which is important as such knowledge can reduce reliance on chemical means of control and thus associated environmental threats. Breaking of pest and disease cycles is more effective the greater the taxonomic separation of sequential crops, thus the value of cereal-legume rotations as compared to rotations of different gramineous crops. For example, crown rot of wheat (caused by *Fusarium graminearum*) in northern New South Wales, Australia, was worse when the crop followed wheat (mean 30%) than when it followed chickpea (mean 12%) (Felton *et al.*, 1998). The severity of leaf spot diseases of wheat is less when wheat is grown after lentil than after wheat (Fernandez *et al.*, 1998). In some situations, non-N beneficial effects can be substantial.

Stevenson and van Kessel (1996) explained only 8% of the rotational benefit of pea as being due to residual N. The remaining 92% benefit was attributed to pea reducing incidence of wheat diseases in this area of Saskatchewan, Canada, but the authors suggested that more work was required to clarify and quantify non-N effects. Nematodes are particularly difficult to control by chemical means and crop rotations, preferably including crops not preferred by the particular nematode, remain the major control method (Sasser and Uzzell, 1991).

Crop rotation introduces conditions unfavorable for particular weed species, which disturbs their growth and reproduction patterns. For example, inclusion of soybean in rotation with maize and wheat reduces incidence of *Setaria* spp. weeds in the cereal crops (Schreiber, 1992). In tropical cropping systems, pigeonpea grown as an intercrop with cereals such as sorghum can effectively suppress weeds, as compared with sole cereal crops (Rao and Shetty, 1996). Liebman and Dyck (1993) concluded that the success of rotations for weed suppression depends on the use of crop sequences that create varying patterns of resource competition, allelopathic interference, soil disturbance and mechanical damage that provides an adverse and unstable environment for particular weed species. This also applies to parasitic weeds in that Carsky *et al.* (2000) reported reduced *Striga hermonthica* parasitism on maize following soybeans compared with a sorghum control. In weed management in conservation tillage systems, judicious combination of herbicide use and crop rotation is recommended (Worsham and White, 1987).

Problems of including Legumes in Cropping Systems

Although many benefits of including legumes in cropping systems can be documented, as above, there are also some detrimental effects of incorporating legumes. Due to the overall risks associated with growing legume crops, their inclusion in cropping systems can increase overall risks of the system. Some specific problems of including legumes are as follows.

Soil Acidification

Soil acidification as a result of legume cultivation, both pasture and grain legumes, is an increasing problem in temperate Australia at least. This is attributed to leaching of nitrate, derived from biological N_2 fixation, causing a net efflux of H^+ from legume roots (Helyar and Porter, 1989). Increasing soil acidity reduces crop growth and yields through a range of mechanisms, such as decreasing availability of nutrients like Mo and P, increasing toxicities of Al and Mn, and direct adverse effects of H^+ on root function. With lupin-wheat and clover-wheat rotations in south-eastern Australia, Heenan and Taylor (1995) observed soil pH to decline from around 4.9 to around 4.3 over a period of 8-9 years. There are large differences between pasture legumes in their ability to produce H^+, with total ash alkalinity and total excess cations in shoots providing a good indicator of total proton production (Table 11) (McLay *et al.*, 1997). Chickpea and narrow-leafed lupin had the highest acidification level and fieldpea the least. Management options to minimize soil acidification rates include early sowing of cereals to reduce nitrate leaching, strategic use of N fertilizers (matching dose and timing to plant demand), reduced tillage, stubble incorporation, liming, and restricted use of legume species/cultivars with high acidification potential.

Table 11. Specific H^+ production by roots and excess cations in shoots in grain legumes grown for 36 days in solution culture (from McLay *et al.*, 1997)

Grain legume cmol kg^{-1}	Specific H^+ production cmol kg^{-1}	Excess cations†
Pilosus	100	139
Yellow lupin	102	119
White lupin	81	121
Narrow-leafed lupin	119	167
Fababean	85	145
Fieldpea	77	116
Grasspea	106	122
Chickpea	136	177
Common vetch	105	126
Lentil	89	ND‡
Least significant difference (P = 0.05)	16	

† Samples from three replicates were bulked; ‡ Not determined due to insufficient sample.

Soil Water Depletion

When legumes replace fallow, to be followed by a cereal crop, one of the advantages of fallow is compromised, namely the availability of stored soil moisture for the following cereal. For example, in the semi-arid northern Great Plains of the USA, Nielsen and Vigil (2005) found that when pea, lentil or vetch replaced the normal summer fallow, soil moisture levels were reduced in legume plots to the extent of causing yield reductions in the following winter wheat crop. Any positive effects of legume cultivation, such as N and soil organic matter accretion, were negated by their use of scarce stored soil moisture resources in this environment. On the other hand, when the legume replaces a crop that extracts more water than that legume then more residual moisture is left for the following crop. For example, in the semi-arid northern Great Plains of Canada, higher yields of canola or mustard when grown after pea or lentil, as compared with after mustard or wheat, were attributed to increased available water (Miller *et al.*, 2003). There is considerable variation in the pattern of water use and water use efficiency among grain legumes crops (Zang *et al.*, 2000; Siddique *et al.*, 2001) and correct choice of legume species in the cropping system can over come some of the above problems.

Susceptibility, Pests, Diseases and Weeds

Repeated cultivation of a particular legume may cause build-up of a certain pests and diseases of that legume. If such pests and diseases also affect other crop species grown in the rotation then cultivation of the legume can be detrimental to the overall cropping system. For example, the foliar disease Botrytis grey mould (caused by *Botrytis cinerea*) and pod borer (*Helicoverpa armigera*) are severe constraints to chickpea but they can be propagated in the chickpea crop and affect subsequent and adjacent crops. It is abundantly evident that one of the major reasons why grain legume crops have limited adoption is that they are poorly competitive against weed species especially in extensive agriculture (Walsh *et al.,* 2004). For example in Australia due to the extensive development of herbicide resistance growers are reluctant to expand their precious herbicide resources (years that a herbicide is effective before resistance develops) on grain legume crops. In the short to medium term, it is unlikely that grain legume crops will realize their full potential in such farming systems until the industry has access to sustainable weed management packages (Walsh *et al*., 2004).

Socioeconomics of including Legumes

Profitability

Whether in commercialized or subsistence agriculture farmers' decisions to increase area sown to grain legumes depend on the profitability of those legumes in relation to alternative crop options. As an example, inclusion of chickpea in a wheat cropping system (one year chickpea and two years wheat) in the northern cereal belt of New South Wales, Australia more than doubled gross margins over the traditional pattern of either continuous wheat or two years wheat and one year fallow (Peoples *et al*., 1995). In a rainfed rice-based system in Bangladesh, inclusion of chickpea after rice has been shown to be relatively profitable (Saha, 2002). This is certainly the case in totally rainfed systems when chickpea replaces fallow but also when it replaces irrigated winter crops like rice, wheat and mustard. There are many examples of greater profitability of including grain legumes in existing cropping systems but the extent to which farmers exploit them depends on the degree of their knowledge of that potential profitability and optimum cultivation techniques; this knowledge is only sparingly available in subsistence agricultural systems.

The above calculations on grain legume profitability only take account of income from grain, and in some cases stover. The examples referred to earlier in this paper indicate that there should be economic advantages resulting from inputs of fixed N and also non-N residual effects, but these are rarely calculated. In assessing the economics of N in farming systems in eastern Australia, Brennan and Evans (2001) calculated that fixed N derived from either narrow-leaf lupins or field pea was generally cheaper than N derived from fertilizer, especially over the longer term (Table 12). However, as the amount of residual fixed N can vary markedly over space and time, such calculations are very site specific. Farmers need to make such calculations for specific situations before informed decisions about fertilizer requirements can be made (Brennan and Evans, 2001). With recent rapid increases in the cost of fossil fuels, and hence fertilizer N, these calculations would shift much more favorably towards fixed N as a cheaper source of N than fertilizer N. These calculations do not take account of the non-N benefits of these legumes, as these are even more difficult to quantify and subject to economic analysis than N benefits.

Risk

Crop diversification, which usually involves leguminous crops in the cropping sequence, is generally thought to reduce economic risks. There is evidence that this is the case in commercial agriculture. For example, Cutforth *et al.* (2001) found greater crop diversity in Nebraska, USA, on sloping than on flat land. Cropping is more risky on sloping land and

Table 12. Calculated real cost of N derived from different sources in New South Wales, Australia, 1999 (from Brennan and Evans, 2001)

N source	Following crop A$ kg N^{-1}	Longer term A$ kg N^{-1}
Fertilizers		
Urea	1.85	1.10
Di-ammonium phosphate (P required)	1.87	1.16
Mono-ammonium phosphate (P required)	2.59	1.67
Di-ammonium phosphate (P not required)	6.49	3.73
Mono-ammonium phosphate (P not required)	11.65	6.71
Ammonium sulphate	4.63	2.81
Ammonium nitrate	2 92	1.64
Legumes		
Narrow-leaf lupins (replacing canola)	3.63	0.92
Narrow-leaf lupins (replacing wheat)	2.72	0.70
Fieldpeas (replacing canola)	2.40	0.63
Fieldpeas (replacing wheat)	0.92	0.27

farmers there generally have lower farm incomes than those on the more fertile flat land. Similarly, in Montana, USA, crop diversification with grain legumes lowered production risks (Miller and Holmes, 2005). In Canada, Johnston *et al.* (2005) showed that rotations involving wheat and broadleaf crops, including pea, were less risky than continuous cropping. They attributed this primarily to disease effects when a crop is sown on its own stubble. Zentner *et al.* (2002) showed that inclusion of oilseeds and pulses in crop rotations with cereals contributed to higher and more stable farm income in most soil-climate regions, despite a requirement for increased expenditures on purchased inputs. This is in the context of summer-fallow replacement and a shift to conservation tillage practices. In Canada, the trend to less risky cropping by including oilseeds and pulses is greater on grey and black soils rather than brown soils where conservation tillage is not so effective.

Medium term weather forecasting and availability of inputs for a range of crop options to permit decision making when the season breaks have been used to determine risk factors in growing grain legumes in the eastern wheatbelt area of Western Australia (Schilizzi and Kingwell, 1999). The stochastic bioeconomic farming system model MUDAS (Model of an Uncertain Dryland Agricultural System) was then applied to the soil and climate risk information, including scenarios for price changes. For a typical farm, inclusion of chickpea in a primarily wheat based cropping system, under standard agronomic assumptions, increased farm profit by 7%. Net income variance, under a range of agroecological and price scenarios, was less for chickpea than the other grain legumes being compared, faba bean and pea. The APSIM model has also been used to assess risk and profitability of rotations chickpea and mung bean with cereals in eastern Australia (Carberry, 1995). Such analyses are recommended to unravel the mysteries of "risk" and thus allow farmers to make rational choices on crop allocation within their land in relation to profit maximization *vs* risk.

Crop diversification is a method of coping with risk, especially for low resource enterprises, as it would lower the variance of farm income should one crop give poor results in a year. However, for a farmer to diversify beyond an existing cropping pattern, knowledge of the agronomic requirements and likely profitability of a new crop, ready availability of the required inputs (especially quality seed but also fertilizers, pesticides, etc.) and market outlets, is needed. These requirements are more likely to be met in large scale developed agriculture, as evidenced by the rapid uptake of various, new grain legumes in Australia over the previous 25 years (Siddique and Sykes, 1997; Siddique *et al.*, 1999). In resource-poor, predominantly subsistence situations, these conditions are invariably not in place and adoption of new cropping options generally proceeds at a slow pace. Thus, although it can be shown that crop diversification can increase farm income and lower the risk of income variance, resource-poor farmers often face the risks caused by inadequate knowledge about, and infrastructure to support, alternative options.

Input Supply and Markets

For resource-poor farmers to adopt or increase cultivation of a grain legume, the major constraint is usually availability of quality seed of an improved variety. Infusion of such seed usually depends on implementation of a development project. Similarly, if agro-chemical inputs required for the legume are any different from those already being sold for existing crops, lack of timely availability of these would hinder adoption. Any venture into a new crop, or expansion of an existing one, would require the promise of stable and remunerative prices and existence of adequate market facilities. These conditions are often not available for resource-poor farmers, especially those at a distance from transport infrastructure. However, it often the information about availability of inputs and markets which is the major discouragement to resource-poor farmers in diversifying their cropping with grain legumes.

Possibilities for Poverty Alleviation

Cultivation of grain legumes provides a good candidate for rural poverty alleviation. While there is a continuing requirement for ever-increasing production of staple cereals, the economics of these crops, particularly in the case of rice, allow little opportunity for cultivators to lift themselves from poverty through reliance on these crops. Global and local prices of crops such as rice and wheat are on a long term downward trend but cost of inputs for these crops are steadily increasing, especially with respect to N fertilizer. On the other hand, grain legume prices are mostly increasing, due to scarcity of production, and their input requirements are more modest than those of cereals (e.g. no requirement for irrigation or N fertilizer). Grain legumes also offer opportunities for on-farm value addition, such as seed drying and cleaning, *dhal* making and packaging, activities offering income generation opportunities for women in particular.

Consequences for Human Nutrition

There is increasing awareness of the role of cropping systems in supplying humans with their essential nutrients (Welch, 2004). Cereal dominated diets fall short in meeting the requirements for many of these nutrients and, in many developing countries, traditional sources of nutrients from animal or fish products are becoming more scarce and unaffordable. Many grain legumes contain high enough concentrations of some vitamins and essential elements, present only at low levels in cereals, to meet human needs. Per capita availability of grain legumes has also declined in most developing countries at least. Some nutrients in higher concentration in legume grain, as compared to cereal grain, include protein and some essential amino acids, calcium, phosphorus, zinc, iron and cobalt. There is an urgent need to increase grain legume cultivation generally to firstly restore and then improve nutritional status and health of humans.

Increasing Grain Legume Use in Cropping Systems

Elements of Required Endeavors

In large-scale commercialized agriculture in developed countries there are many recent examples of expansion of grain legume expansion in recent years, e.g. Australia, Canada. Here the constraints related to appropriate technology, information dissemination to farmers, availability of markets, etc. are much less than in developing countries and thus rapid adoption of new crops and technologies is possible. To expand grain legume cultivation among resource-poor farmers in developing countries however, systematic efforts are needed to overcome the major constraints involved. The key elements involved are:

- Technology adaptation such that it is appropriate for resource-poor farmers, with low cost of inputs a major criterion. An example is the use of seed priming (soaking of seed overnight prior to sowing) of chickpea in the High Barind Tract of Bangladesh to enhance seedling establishment in rapidly drying seedbeds, and ultimately increase yield (Musa *et al.*, 2001).
- Development of village level seed production schemes to ensure adequate local supply of quality seed.
- Ensure farmer (including the whole farm family) participation in technology development and evaluation and demonstration process, such that they feel ownership of the technology at an early stage.
- Ensure sub-sector coordination for input availability and market access. A business development services (BDS) approach is recommended for this purpose, whereby bottleneck constraints of the sub-sector are identified and tackled (Lusby and Panlibuton, 2004). Deficiencies in input availability are tackled by developing local entrepreneurship to profitably supply the required inputs, rather than expecting government intervention to provide them.
- Ensure access to relatively stable markets with a means of rapidly informing growers of current prices and trends.
- Ensure information availability to prospective growers with respect to economic assessment of growing the crop, technology required, access to on-farm demonstrations, marketing, etc.

- Provide on-going technical monitoring and research back-up for problems arising. A particularly important consideration is to ensure adequate and ongoing performance of the legume-*Rhizobium* symbiosis and therefore reap the benefits of N fixation (Howieson *et al.*, 2000). Also important is the ever-evolving suite of pests and diseases the grain legumes are exposed to.

Examples of Successful Attempts

Despite constraints faced by resource-poor farmers in expanding their grain legume production, there are some examples of recent crop diversification with grain legumes. Firstly, there is the rapid expansion of blackgram that has occurred in rice fallows of eastern India (Satyanarayana *et al.*, 2001). Main reasons for this success were ability to manage foliar diseases, through both fungicide use and resistant varieties, and farmer involvement in the research to development process. The advent of short duration mungbean varieties has provided a niche for this crop between harvest of wheat and transplanting of rice in intensive, irrigated rice wheat cropping systems of the Indo-Gangetic Plain (Johansen *et al.*, 2000). The development of short duration pigeonpea has also given respite to intensive rice-wheat rotations in India (Singh *et al.*, 2005). Short duration pigeonpea can substitute rice in the rotation without any detriment to farmers' income and with rotational benefits to the following wheat crop, and subsequent cereal crops.

In the late 1990s, a serious epidemic of Botrytis grey mould (BGM) devastated the chickpea crop in Nepal. The crop has since been rehabilitated through on-farm evaluation and demonstration of BGM management techniques, combined with other improved crop management procedures (e.g. pod borer control, alleviation of boron deficiency, etc.) (Pande *et al.*, 2003). Chickpea cultivation has expanded in the High Barind Tract of Bangladesh over the previous two decades, as a result of introduction of improved technologies (e.g. new varieties, seed priming, pod borer management), farmer-managed evaluation and demonstration of these, and development of local seed production schemes (Musa *et al.*, 2001).

Conclusion

There is now a formidable array of evidence quantifying the benefits of including grain legumes in cropping systems for increased cropping system productivity and environmental sustainability. A suite of technologies is also available to allow successful legume cultivation in a range of cropping systems, in developed and developing countries. However, there is a dearth of analyses quantifying the economic advantages involved in increasing grain legume cultivation. Lack of awareness of economic benefits is a major constraint to increased adoption. Cropping system models provide frameworks for such economic analyses but innovative means of presentation of outcomes to farmers are needed. Profitabilities and probabilities of success of a range of options need to be clearly presented to farmers.

There is a particular need to factor in the economic value of residual benefits. The value of fixed N is substantially increasing as fossil fuel prices increase, and this needs to be highlighted. Further, non-renewable energy requirements for agriculture need to be considered; Zentner *et al.* (2004) showed that use of pulses decreases non-renewable energy requirement under conservation tillage systems in Canada, due to both reduced tillage and reduced need of fertilizer N. However, reliable economic evaluation of non-N benefits will probably require further biophysical data.

A major reason for stagnation or decline in plantings of most grain legumes is the build up of various biotic constraints after repeated cultivation at the same location. Research emphasis is therefore required in this area, in seeking host plant resistance and exploring agronomic management options. However, to hasten the adoption of seemingly worthwhile technology by resource-poor farmers in developing countries, on-farm, farmer-participatory adaptive research approaches are required, to a much greater extent than currently being implemented. Many potential solutions to biotic constraints of all of the target legumes have been researched but few find their way into the fields of resource-poor farmers. Widespread farmer evaluation of this information is required, with on-going interaction among extension personnel, researchers and farmers; into the indefinite future due to the continued evolution of biotic stresses, now catalyzed by climate change.

References

Ae, N., J. Arihara, K. Okada, T. Yoshihara and C. Johansen. 1990. Phosphorus uptake by pigeonpea and its role in cropping systems of the Indian subcontinent. Science, 248: 477-480.

Ae, N., J. Arihara and K. Okada. 1991. Phosphorus response of chickpea and evaluation of phosphorus availability in Indian alfisols and vertisols. p. 33-41. *In* C. Johansen *et al.* (ed.). Phosphorus nutrition of grain legumes in the semi-arid tropics. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 234 India.

Ahlawat, I.P.S., M. Ali, R.L. Yadav, J.V.D.K. Kumar Rao, T.J. Rego and R.P. Singh 1998. Biological nitrogen fixation and residual effects of summer and rainy season grain legumes in rice and wheat cropping systems of the Indo-Gangetic Plain. p. 31-54. *In* J.V.D.K. Kumar Rao *et al.* (ed.). Residual effects of legumes in rice and wheat cropping systems of the Indo-Gangetic Plain. ICRISAT, Patancheru, India; and Oxford and IBH, New Delhi, India

Ahlawat, I.P.S., C.S. Saraf and A. Singh. 1977. Studies on the effect of *rabi* grain legumes on fertilizer N economy of *kharif* cereal (maize). p. 23. *In* Half yearly report ending December 1977, Division of Agronomy, Indian Agricultural Research Institute, New Delhi, India (Limited circulation).

Amrani, M., D.G. Westfall and L. Moughli 2001. Phosphorus management in continuous wheat and wheat-legume rotations. Nutr. Cycl. Agrecosys, 59: 19-27.

Arihara, J., N. Ae and K. Okada 1991. Root development of chickpea and pigeonpea and its significance in different cropping systems. p. 183-194. *In* C. Johansen *et al.* (ed.). Phosphorus nutrition of grain legumes in the semi-arid tropics. ICRISAT, Patancheru, India.

Armstrong, E.L., D.P. Heenan, J.S. Pate and M.J. Unkovich 1997. Nitrogen benefits of lupins, field pea, and chickpea to wheat production in south-eastern Australia. Aust. J. Agric. Res., 48: 39-47.

Aslam, M., I.A. Mahmood, M.B. Peoples, G.D. Schwenke and D.F. Herridge 2003. Contribution of chickpea nitrogen fixation to increased wheat production and soil organic fertility in rain-fed cropping. Biol. Fertil. Soils, 38: 59-64.

Bandyopadhyay, S.K. and R. De. 1986. Nitrogen relationships and residual effects of intercropping sorghum with legumes. J. Agric. Sci., Camb., 107: 629-632.

Beckie, H.J. and S.A. Brandt. 1997. Nitrogen contribution of field pea in annual cropping systems. 1. Nitrogen residual effect. Can. J. Plant Sci., 77: 311-322.

Biederbeck, V.O., R.P. Zentner and C.A. Campbell. 2005. Soil microbial populations and activities as influenced by legume green fallow in a semiarid climate. Soil Biol. Biochem., 37: 1775-1784.

Blevins, R.L., J.H. Herbek and W.W. Fyre. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J., 82: 769.

Boddey, R.M., S. Urquiaga, M.C. Neves, A.R. Suhet and J.R. Peres. 1990. Quantification of the contribution of N_2 fixation to field-grown legumes – a strategy for the practical application of the ^{15}N isotope dilution method. Soil Biol. Biochem., 22: 649-655.

Brennan, J.P. and Evans, J. 2001. Measuring the relative economic costs of legume and fertilizer nitrogen. Aust. J. Exp. Agric., 41: 383-390.

Bruce, R.R., S.R. Wilkinson and G.W. Langdale. 1987. Legume effects on soil erosion and productivity. p. 127-138. *In* J.F. Power (ed.). Role of legumes in conservation tillage systems. Soil conservation Society of America, Ankeny, Iowa, USA.

Buresh, R.J. and S.K. De Datta. 1991. Nitrogen dynamics and management in rice-legume cropping systems. Adv. Agron., 45: 1-59.

Campbell, C.A. and R.P. Zentner. 1993. Soil organic matter as influenced by crop rotations and fertilization. Soil Sci. Soc. Am. J., 57: 1034-1040.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich and B. Blomert. 2000. Organic C accumulation in soil over 30 years in semi-arid southwestern Saskatchewan. Effect of crop rotations and fertilizers. Can. J. Soil Sci., 80: 179-192.

Carberry, P.S. 1995. Assessing the opportunity for increased production of grain legumes in the farming system – GRDC Project CSC9. Final Report to Grains Research and Development Corporation for Project No. CSC9.

Carsky, R.J., D.K. Berner, B.D. Oyewole, K. Dashiell and S. Schulz, 2000. Reduction of *Striga hermonthica* parasitism on maize using soyabean rotation. Int. J. Pest Manage, 46: 115-120.

Chalk, P.M. 1998. Dynamics of biologically fixed N in legume-cereal rotations: A review. Aust. J. Agric. Res., 49: 303-316.

Chapman, A.L. and R.J.K. Myers. 1987. Nitrogen contributed by grain legumes to rice grown in rotation on the Cununurra soils of the Ord irrigation area, Western Australia. Aust. J. Exp. Agric., 27: 155-163.

Christensen, B.T. and A.E. Johnston. 1997. Soil organic matter and soil quality – lessons learned from long-term experiments at Askov and Rothamsted. p. 399-430. *In* E.G. Gregorich and M.R. Carter (ed.). Soil quality for crop production and ecosystem health. Elsevier, Amsterdam, The Netherlands.

Conner, D.J. 2001. Optimizing crop diversification. p. 191-211. *In* J. Nösberger *et al.* (ed.). Crop science: progress and prospects. CABI Publishing, Wallingford, UK.

Cutforth, L.B., C.A. Francis, G.D. Lynne, D.A. Mortensen and K.M. Eskridge. 2001. Factors affecting farmers' crop diversity decisions: an integrated approach. Amer. J Altern. Agric., 16: 168-176.

Dakora, F.D., R.A. Aboyinga, Y. Mahama and J. Apaseku. 1987. Assessment of N_2-fixation in groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata* L.Walp) and their relative N contribution to a succeeding maize crop in Northern Ghana. MIRCEN J., 3: 389-399.

Danso, S.K.A. and I. Papastylianou 1992. Evaluation of the nitrogen contribution of legumes to subsequent cereals. J. Agric. Sci., 119: 13-18.

Date, R.A. 2000. Inoculated legumes in cropping systems of the tropics. Field Crops Res., 65: 123-136.

De, R., Y. Yogeswara and W. Ali 1983. Grain and fodder legumes as preceding crops affecting the yield and N economy of rice. J. Agric. Sci. Camb., 101: 463-466.

Doughton, J. A. and J. MacKenzie. 1984. Comparative effects of black and green gram (mung beans) and grain sorghum on soil mineral nitrogen and subsequent grain sorghum yields on the eastern Darling Downs. Aust. J. Exp. Agric. Anim. Husb., 24: 244-249.

Doughton, J. A., I. Vallis and P.G. Saffigna. 1993. Nitrogen fixation in chickpea. I. Influence of prior cropping or fallow, nitrogen fertilizer or tillage. Aust. J. Agric. Res., 44: 1403-1413.

Eaglesham, A.R.J., A. Ayanaba, V. Ranga Rao and D.L. Eskew. 1981. Improving the nitrogen nutrition of maize by intercropping with cowpea. Soil Biol. Biochem., 13: 169-171.

Evans, J., A.M. McNeill, M.J. Unkovich, N.A. Fettell and D.P. Heenan. 2001. Net nitrogen balances for cool-season grain legumes crops and contributions to wheat nitrogen uptake: a review. Aust. J. Exp. Agric., 41: 347-359.

Evans, J., G. Scott, D. Lemerle, A. Kaiser, B. Orchard, G.M. Murray and E.L. Armstrong. 2003. Impact of legume "break crops" on the yield and grain quality of wheat and relationship with soil mineral N and crop N content. Aust. J. Agric. Res., 54: 777-788.

FAO (Food and Agriculture Organization of the United Nations). 2005. http://faostat.fao.org/faostat/form?collection=Production.Crops.Primary&Domain=Production&servlet=1&hasbulk=&version=ext&language=EN. Accessed 15 June 2005.

Felton, W.L., H. Marcellos, C. Alston, R.J. Martin, D. Backhouse, L.W. Burgess and D.F. Herridge. 1998. Chickpea in wheat-based cropping systems of northern New South Wales. II. Influence on biomass, grain yield, and crown rot in the following wheat crop. Aust. J. Agric. Res., 49: 401-407.

Femandez, M.R., R.P. Zentner, B.G. McConkey, and C.A. Campbell. 1998. Effects of crop rotations and fertilizer management on leaf spotting diseases of spring wheat in southwestern Saskatchewan. Can J. Plant Sci., 78: 489-496.

Francis, C.A. (ed.). 1986. Multiple Cropping Systems. Macmillan, New York, USA.

Fyson, A. and A. Oaks. 1990. Growth promotion of maize by legume soils. Plant Soil, 122: 259-266.

Gardner, W.K, D.G. Parbery and D.A. Barber. 1981. Proteoid root morphology and function in *Lupinus albus*. Plant Soil, 60: 143-147.

George, M. and R. Prasad. 1989. Studies on the effect of cereal-cereal and cereal-legume cropping system on the productivity and fertility of soil. Fert. News, 34: 21-25.

George, T., J.K. Ladha, D.P. Garrity and R.O. Torres. 1995. Nitrogen dynamics of grain legume-weedy fallow flooded rice sequences in the tropics. Agron. J., 87: 1-6.

Gerke, J., W. Römer and A. Jungk 1994. The excretion of citric and malic acid by proteoid roots of *Lupinus albus* L.: Effect on soil solution concentrations of phosphate, iron and aluminium in the proteoid rhizosphere in samples of an oxisol and a luvisol. Z. Pflanzenernäh. Bodenk., 157: 289-294.

Giller, K.E., F. Amijee, S.J. Brodrick and O.T. Edje. 1998. Environmental constraints to nodulation and nitrogen fixation of *Phaseolus vulgaris* L. in Tanzania. II.Response to N and P fertilizers and inoculation. African J. Crop Sci., 6: 171-178.

Gowda, C.L.L., A. Ramakrishna, O.P. Rupela and S.P. Wani 2001. Legumes in rice-based cropping systems in tropical Asia: Constraints and opportunities. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 234 India.

Graham, P.H. and J.C. Rosas. 1978. Plant and nodule development and nitrogen fixation in climbing cultivars of *Phaseolus vulgaris* L. grown in monoculture or associated with *Zea mays* L. J. Agric. Sci., Camb., 90: 311-317.

Gull, M., F.Y. Hafeez, M. Saleem and K.A. Malik. 2004. Phosphorus uptake and growth promotion of chickpea by co-inoculation of mineral phosphate solubilising bacteria and a mixed rhizobial culture. Aust. J. Exp. Agric., 44: 1-6.

Hafeez, F.Y., T. Ahmed, T. Asad, K. Malik, N.H. Shah and S.K.A. Danso. 1998. Field evaluation of N_2 fixation by grain legumes in Pakistan. p. 41-56. *In* Improving yield and nitrogen fixation of grain legumes in the tropics and sub-tropics of Asia. International Atomic Energy Agency, Vienna, Austria.

Hamblin, J.. R. Delane, A. Bishop and G. Adam. 1993. The yield of wheat following lupins: Effects of different lupin genotypes and management Aust. J. Agric. Res., 44: 645-659.

Hardarson, G., F.A. Bliss, M.R. Cigales-Rivero, R.A. Henson, J.A. Kipe-Nolt, L. Longeri, A. Manrique, J.J. Pena-Cabriales, P.A.A. Pereira, C.A. Sanabria and S.M. Tsai. 1993. Genotypic variation in biological nitrogen fixation by common bean. Plant Soil, 152: 59-70.

Harrier, L.A. and C.A. Watson. 2003. The role of arbuscular mycorrhizal fungi in sustainable cropping systems. Adv. Agron., 79: 185-225.

Heenan, D.P. and A.C. Taylor. 1995. Soil pH decline in relation to rotation, tillage, stubble retention and nitrogen fertilizer in S.E. Australia. Soil Use Manag., 11: 4-9.

Helyar, K.R. and W.M. Porter. 1989. Soil acidification, its measurement and processes involved. p. 61-100. *In* A.D. Robson (ed.). Soil acidity and plant growth. Academic Press, Sydney, Australia.

Herridge, D.F., H. Marcellos, W.L Felton, G.L. Turner and M.B. Peoples. 1995. Chickpea increases soil-N fertility in cereal systems through nitrate sparing and N_2 fixation. Soil Biol. Biochem., 27: 545-551.

Herridge, D.F., H. Marcellos, W.L Felton, G.L. Turner, and M.B. Peoples 1998. Chickpea in wheat-based cropping systems of northern New South Wales. III. Prediction of N_2 fixation and N balance using soil nitrate at sowing and chickpea yield. Aust. J. Agric. Res., 49: 409-418.

Hocking, P.J. and Randall, P.J. 2001. Better growth and phosphorus nutrition of sorghum and wheat following organic acid secreting crops. p. 548-549. *In* W.J. Horst *et al.* (ed.). Plant nutrition – food security and sustainability of agro-ecosystems. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Horst, W.J., M. Kahm, J.M. Jibrin and V.O. Chude. 2001.Agronomic measures for increasing P availability to crops. Plant Soil, 237: 211-223.

Howieson, J.G., G.W. O'Hara and S.J. Carr. 2000. Changing roles for legumes in Mediterranean agriculture: developments from an Australian perspective. Field Crops Res., 65: 107-122.

Jensen, E.S. 1996. Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops. Plant Soil, 182: 25-38.

Johansen, C., J.M. Duxbury, S.M. Virmani, C.L.L. Gowda, S. Pande and P.K. Joshi. 2000. Legumes in rice and wheat cropping systems of the Indo-Gangetic Plain – constraints and opportunities. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 234 India and Cornell University, Ithaca, New York, USA.

Johnston, A.E. 1991. Soil fertility and organic matter. p. 299-313. *In* W.S. Wilson (ed.). Advances in soil organic matter research: the impact on agriculture and the environment. Roy. Soc. Chem., U.K.

Johnston, A.M., H.R. Kutcher and K.L. Bailey. 2005. Impact of crop sequence decisions in the Saskatchewan Parkland. Can. J. Plant Sci., 85: 95-102.

Karlen, D.L., G.E. Varvel, D.G. Bullock and R.M. Cruse. 1994. Crop rotations for the 21st century. Adv. Agron., 53: 1-45.

Khan, D.F., D. Chen, D.H. Herridge, G.D. Schwenke and M.B. Peoples. 2000. Contribution of below-ground legume N to crop rotations. p. 33-34. *In* Proceedings of the International Symposium on Nuclear Techniques in Integrated Plant Nutrient, Water and Soil Management. IAEA, Vienna, Austria.

Kho, R.M. 2000. On crop production and the balance of available resources. Agric. Ecosys. Environ., 80: 71 85.

Kucey, R.M.N., P. Chaiwanakupt, T. Arayangkool, P. Snitwongse, C. Siripaibool, P. Wadisirisuk and N. Boonkerd. 1988. Nitrogen fixation (^{15}N dilution) with soybeans under Thai field conditions.II. Effect of herbicides and water application schedule. Plant Soil, 108: 87-92.

Kumar Rao, J.V.D.K., P.J. Dart and P.V.S.S. Sastry. 1983. Residual effect of pigeonpea (*Cajanus cajan*) on yield and nitrogen response of maize. Exp. Agric., 19: 131-141.

Kumar Rao, J.V.D.K. and P.J. Dart. 1987. Nodulation, nitrogen fixation and nitrogen uptake in pigeonpea [*Cajanus cajan* (L.) Millsp.] of different maturity groups. Plant Soil, 99: 255-266.

Kumar Rao, J.V.D.K., J.A. Thompson, P.V.S.S. Sastry, K.E. Giller and J.M. Day. 1987. Measurement of N_2-fixation in field-grown pigeonpea [*Cajanus cajan* (L.) Millsp.] using ^{15}N-labelled fertilizer. Plant Soil, 101: 107-113.

Kumar Rao, J.V.D.K., C. Johansen, T. Yoneyama, S. Tobita and O. Ito, 1996. Estimation of nitrogen fixation by the natural ^{15}N-abundance technique and nitrogen uptake by pigeonpea genotypes of different maturity groups grown in an Inceptisol. J. Agron. Crop Sci., 177: 129-138.

Kumar Rao, J.V.D.K. and O.P. Rupela. 1998. Factors affecting biological nitrogen fixation and residual effects of legumes in the Indo-Gangetic Plain. p. 82-104. *In* J.V.D.K. Kumar Rao *et al.* (ed.). Residual Effects of Legumes in Rice and Wheat Cropping Systems of the Indo-Gangetic Plain. ICRISAT, Patancheru, India; and Oxford and IBH, New Delhi, India.

Kumar Rao, J.V.D.K., C. Johansen and T.J. Rego. 1998. Residual effects of legumes in rice and wheat cropping systems of the Indo-Gangetic Plain. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 234 India; and Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, India.

Ladha, J.K., D.K. Kundu, M.G. Angelo-Van Coppenolle, M.B. Peoples, V.R. Carangal and P.J. Dart. 1996. Legume productivity and soil nitrogen dynamics in lowland rice-based cropping systems. Soil Sci. Soc. Am. J., 60: 183-192.

Ladha, J.K., A. Tirol-Padre, G.C. Punzalan, M. Garcia and I. Watanabe. 1989. Effect of inorganic N and organic fertilizers on nitrogen-fixing (acetylene-reducing) activity associated with wetland rice-plants. p. 263-272. *In* F.A. Skinner *et al.* (ed.). Nitrogen fixation with non-legumes. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Latif, M.A., G.R. Mehuys, A.F MacKenzie, I. Ali and M.A. Faris. 1992. Effects of legumes on soil physical quality in a maize crop. Plant Soil, 140: 15-23.

Lauren, J.G., J.M. Duxbury, V. Beri, M.A. Razzaque II, M.A. Sattar, S.P. Pandey, S. Bhattarai, R.A. Mann and J.K. Ladha. 1998. Direct and residual effects from forage and green manure legumes in rice-based cropping systems. p. 55-81. *In* J.V.D.K. Kumar Rao *et al.* (ed.). Residual effects of legumes in rice and wheat cropping systems of the Indo-Gangetic Plain. ICRISAT, Patancheru, India; and Oxford and IBH, New Delhi, India.

Li, L., C. Tang, Z. Rengel and F.S. Zhang. 2003a. Chickpea facilitates phosphorus uptake by intercropped wheat from an organic phosphorus source. Plant Soil, 248: 297-303.

Li, L., F.S. Zhang, X.L. Li, P. Christie, J.H. Sun, S.C Yang and C. Tang. 2003b. Interspecific facilitation of nutrient uptake by intercropped maize and faba bean. Nut. Cycl. Agroecosys., 65:61-71.

Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecol. Appl., 3: 92-122.

Lusby, F. and H. Panlibuton. 2004. Promotion of commercially viable solutions to subsector and business constraints. Office of Microenterprise Development, USAID/G/EGAD/MD, Washington DC, USA.

Mapfumo, P., K.E. Giller, S. Mpepereki and P.L. Mafongoya. 1999. Dinitrogen fixation by pigeonpea of different maturity types on granitic sandy soils in Zimbabwe. Symbiosis, 27: 305-318.

Marcellos, H. 1984. Influence of prior crops of chickpeas, fababeans and lupins on wheat. J. Aust. Inst. Agric. Sci., 50: 111-113.

Marcellos, H., W.L. Felton and D.F. Herridge. 1998. Chickpea in wheat-based cropping systems of northern New South Wales. I. N_2 fixation and influence on soil nitrate and water. Aust. J. Agric. Res., 49: 391-400

Maskey, S., S. Bhattarai, M.B. Peoples and D.F. Herridge. 1997. Nitrogen fixation by winter and summer legume crops in the hill and terai regions of Nepal. p. 361-371. *In* O.P. Rupela *et al.* (ed.). Extending Nitrogen Fixation Research to Farmers Fields: Proceedings of an International Workshop on Managing Legume Nitrogen Fixation in Cropping Systems of Asia. ICRISAT, Hyderabad, India.

McLay, C.D A., L. Barton and C. Tang 1997. Acidification potential of ten grain legume species grown in nutrient solution. Aust. J. Agric. Res., 48: 1025-1032.

McNeill, A.M., C. Zhu and I.R.F. Fillery. 1997. Use of *in situ* ^{15}N-labelling to estimate the total below-ground nitrogen of pasture legumes in intact soil-plant systems. Aust. J. Agric. Res., 48: 295-304.

McNeill, A.M., M. Unkovich and J. Slattery. 2000. Managing nitrogen fixation inputs by crop, forage and pasture legumes on alkaline soils in southern Australia. Final Report of Grains Research and Development Corporation Project UWA196WR, March 2000.

Meelu, O.P., V. Beri, K.N. Sharma, S.K. Jalota and B.S. Sandhu. 1979. Influence of paddy and corn in different rotations on wheat yield, nutrient removal and soil properties. Plant Soil, 51: 51-57.

Miller, P.R., Y. Gan, B.G. McConkey and C.L. McDonald. 2003. Pulse crops for the Northern Great Plains: I. Grain productivity and residual effects on soil water and nitrogen. Agron J.. 95: 972-979.

Miller, P.R. and J.A. Holmes. 2005. Cropping sequence effects of four broadleaf crops on four cereal crops in the Northern Great Plains. Agron. J., 97: 189-200.

Musa, A.M., D. Harris, C. Johansen and J. Kumar. 2001. Short duration chickpea to replace fallow after *aman* rice: The role of on-farm seed priming in the High Barind Tract of Bangladesh. Exp. Agric., 37: 509-521.

Nambiar, P.T.C., M.R. Rao, M.S. Reddy, C. Floyd, P.J. Dart and R.W. Willey. 1983. Effect of intercropping on nodulation and N_2 fixation by groundnut. Exp. Agric., 19: 79-86.

Nambiar, P.T.C., T.J. Rego and B. Srinivasa Rao 1986. Comparison of the requirements and utilization of nitrogen by genotypes of sorghum [*Sorghum bicolor* (L.) Moench], and nodulating and non-nodulating groundnut (*Arachis hypogaea* L.). Field Crops Res., 15: 165-179.

Nambiar, P.T.C. 1990. Nitrogen nutrition of groundnut in Alfisols. Information Bulletin No. 30. p. 1-30. ICRISAT, Patancheru, A.P., India.

Nielsen, D.C. and M.F. Vigil. 2005. Legume green fallow effect on soil water content at wheat planting and wheat yield. Agron. J., 97: 684-689.

Nuruzzaman, M., H. Lambers, M.D.A. Bolland and E.J. Veneklaas. 2005. Phosphorus benefits of different legume crops to subsequent wheat grown in different soils of Western Australia. Plant Soil, 271: 175-187.

Ofori, F., J.S. Pate and W.R Stern. 1987. Evaluation of N_2 fixation and nitrogen economy of a maize/cowpea intercrop system using ^{15}N dilution methods. Plant Soil, 102: 149-160.

Pala, M., E. Armstrong and C. Johansen. 2000. The role of legumes in sustainable cereal production in rainfed areas. p. 323-334. *In* R. Knight (ed.). Linking research and market opportunities for pulses in the 21st century. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Pande, S., V.A. Bourai and R.K. Neupane. 2003. Wealth generation through chickpea revolution. IPM of chickpea in Nepal – 3. Information Bulletin No. 66. ICRISAT, Patancheru, India.

Patra, D.D., M.S. Sachdev and B.V. Subbaiah. 1986. ^{15}N studies on the transfer of legume-fixed nitrogen to associated cereals in intercropping systems. Biol. Fertil. Soils, 2: 165-171.

Peoples, M.B., F.J. Bergersen, G.L. Turner, C. Sampet, B. Rerkasem, A. Bhromsiri, D.P. Nurhayati, A.W.Faizah, M.N. Sudin, M. Norhayati and D.F. Herridge. 1991. Use of natural enrichment of ^{15}N in plant available soil N for the measurement of symbiotic N_2 fixation. p. 117-130. *In* Stable Isotopes in Plant Nutrition, Soil Fertility and Environmental Studies. IAEA/FAO, Vienna, Austria.

Peoples, M.B. and E.T. Craswell. 1992. Biological nitrogen fixation: investments, expectations and actual contributions to agriculture. Plant Soil, 141: 13-39.

Peoples, M.B., D.F. Herridge and J.K Ladha. 1995. Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production. Plant Soil, 174: 3-28.

Peoples, M.B. 2001. Legume root nitrogen in cropping system nitrogen cycling. Grain Legumes, 33: 8-9.

Peoples, M.B., A.M. Bowman, R.R. Gault, D.F. Herridge, M.H. McCallum, K.M. McCormick, R.M. Norton, I.J. Rochester, G.J. Scammell and G.D. Schwenke. 2001. Factors regulating the contributions of fixed nitrogen by pasture and crop legumes to different farming systems of eastern Australia. Plant Soil, 228: 29-41.

Ram Newaj and D.S. Yadav. 1994. Changes in physico-chemical properties of soil under intensive cropping systems. Indian J. Agron., 39: 373-378.

Rao, C.C.S. and K.D. Singh 1991. Effect of residual greengram [*Vigna radiata* L. Wilczek] after maize-wheat sequence on soil available nitrogen, phosphorus and potassium. Legume Res., 14: 125-130.

Rao, M.R. and S.V.R. Shetty. 1996. Some biological aspects of intercropping system of crop weed balance. Indian J. Weed Sci., 8: 32-43.

Rego, T.J. and V.N. Rao. 2000. Long-term effects of grain legumes on rainy-season sorghum productivity in a semi-arid tropical Vertisol. Exp. Agric., 36: 205-221.

Rego, T.J. and B. Seeling 1996. Long-term effects of legume-based cropping systems on soil nitrogen status and mineralization in Vertisols. p. 469-479. *In* O.Ito *et al.* (ed.). Dynamics of Roots and Nitrogen in Cropping Systems of Semi-Arid Tropics: Japan International Research Center for Agricultural Sciences, Ohwashi, Tsukuba, Japan.

Rerkasem, B., K. Rerkasem, M.B. Peoples, D.F. Herridge and F.J. Bergersen. 1988. Measurement of N_2 fixation in maize (*Zea mays* L.) – ricebean [*Vigna umbellata* (Thumb.) Ohwi and Ohashi] intercrops. Plant Soil, 108: 125-135.

Ries, S.K., V.W.C. Sweeley and R.R. Leavitt. 1977. Tricontanol: A new naturally occurring plant growth regulator. Science, 195: 1339-1341.

Rixon, A.J. 1966. Soil fertility changes in a red brown earth under irrigated pastures. I. Changes in organic carbon, carbon/nitrogen ratio, cation exchange capacity and pH. Aust. J. Agric. Res., 17: 303-316.

Rupela, O.P. and M.C. Saxena. 1987. Nodulation and nitrogen fixation in chickpea. p. 191-206. *In* M.C. Saxena and K.B. Singh (ed.). The chickpea CAB International, Wallingford, UK.

Russell, E.W. 1977. Soil conditions and plant growth. Longman Group Ltd., London, UK.

Sadras, V.O., J.A. Baldock, J.W. Cox and W.D. Bellotti. 2004. Crop rotation effect on wheat grain yield as mediated by changes in the degree of water and nitrogen co-limitation. Aust. J. Agric. Res., 55: 599-607.

Saha, A.K. 2002. Final report on impact assessment study for the DFID-funded Project R7540, "Promotion of chickpea following rainfed rice in the Barind area of Bangladesh". Consultant's Report, DFID Plant Science Research Programme, Centre for Arid Zone Studies, University of Wales, Bangor, UK.

Sanginga, N., K. Dashiell, J.A. Okogun and G. Thottappilly. 1997. Nitrogen fixation and N contribution in promiscuous soybeans in the southern Guinea savanna of Nigeria. Plant Soil, 195: 257-266.

Saraf, C.S., O.P. Rupela, D.M. Hegde, R.L. Yadav, B.G. Shivkumar, S. Bhattarai, M.A. Razzaque II and M.A. Sattar 1998. Biological nitrogen fixation and residual effects of winter grain legumes in rice and wheat cropping systems of the Indo-Gangetic Plain. p.14-30. *In* J.V.D.K. Kumar Rao *et al.* (ed.). Residual effects of legumes in rice and wheat cropping systems of the Indo-Gangetic Plain. ICRISAT, Patancheru, India; and Oxford and IBH, New Delhi, India.

Sasser, J.N. and G. Uzzell Jr. 1991. Control of soybean cyst nematode by crop rotation in combination with a nematicide. J. Nematol., 23: 344-347.

Sattar, M.A., A.K. Podder, M.L. Das, M.A.Q. Shaik and S.K.A. Danso. 1998. Evaluation of chickpea and groundnut for N_2 fixation and yield in Bangladesh. p.131-146. *In* Improving yield and nitrogen fixation of grain legumes in the tropics and sub-tropics of Asia. International Atomic Energy Agency, Vienna, Austria.

Satyanarayana, A., P. Rangaswamy, R. Muttaiah, M.S. Patil, M.V. Reddy, N.V. Naidu, C. Cheralu, A. Ramakrishna, and Y.S. Chauhan. 2001. Legumes in tropical rice-based cropping systems in peninsular India. p. 11-25. *In* C.L.L. Gowda *et al.* (ed.). Legumes in rice-based cropping systems in tropical Asia. Constraints and opportunities. ICRISAT, Patancheru, India.

Schilizzi, S. and R. Kingwell. 1999. Effects of climatic and price uncertainty on the value of legume crops in a mediterranean-type environment. Agric. Sys., 60: 55-69.

Schreiber, M.M. 1992. Influence of tillage, crop rotation, and weed management on giant foxtail (*Setaria faberi*) population dynamics and corn yield. Weed Sci., 40: 645-653.

Schulz, S., J.D.H. Keatinge and J.G. Wells. 1999. Productivity and residual effects of legumes in rice-based cropping systems in a warm-temperate environment. II. Residual effects on rice. Field Crops Res., 61: 37-49.

Schwenke, G.D., M.B. Peoples, G.L. Turner and D.F. Herridge. 1998. Does nitrogen fixation of commercial, dryland chickpea and faba bean in north-west New South Wales maintain or enhance soil nitrogen? Aust. J. Exp. Agric., 38: 61-70.

Senaratne, R. and G. Hardarson. 1988. Estimation of residual N effect of fababean and pea on two succeeding cereals using ^{15}N methodology. Plant Soil, 110: 81-91.

Shah, Z., S. Shah, D.F. Herridge and M.B. Peoples. 1997. Surveys of N_2 fixation of lentil, mung bean and mash bean in farmers' fields in NWFP, Pakistan. p.333-343. *In* O.P. Rupela *et al.* (ed.). Extending Nitrogen Fixation Research to Farmers' Fields: Proceedings of an International Workshop on Managing Legume Nitrogen Fixation in Cropping Systems of Asia. ICRISAT, Hyderabad, India.

Shah, Z., S.H. Shah, M.B. Peoples, G.D. Schwenke and D.F. Herridge. 2003. Crop residue and fertilizer N effects on nitrogen fixation and yields of legume-cereal rotations and soil organic fertility. Field Crops Res., 83:1-11.

Siddique, K.H.M. and J. Sykes. 1997. Pulse production in Australia past, present and future. Aust. J. Exp. Agric., 37: 103-111.

Siddique, K.H.M., S.P. Loss, K.L. Regan and R.L. Jettner. 1999. Adaptation of cool season grain legumes in Mediterranean-type environments of south-western Australia. Aust. J. Agric. Res., 50: 375-387.

Siddique, K.H.M., K.L. Regan, D. Tennant and B.D. Thomson 2001. Water use and water use efficiency of cool season grain legumes in low rainfall Mediterranean-type environments. Europ. J. Agron., 15: 267-280.

Singh, S.B. and B.S. Verma. 1985. Effect of *kharif* grain legumes on nitrogen economy in succeeding crop of wheat. Indian J. Agron., 30: 397-400.

Singh, V.K., B.S. Dwivedi, A.K Shukla, Y.S. Chauhan and R.L. Yadav. 2005. Diversification of rice with pigeonpea in a rice-wheat cropping system on a Typic Ustochrept: Effect on soil fertility, yield and nutrient use efficiency. Field Crops Res., 92: 85-105.

Soon, Y.K. and M.A. Arshad. 2004. Contribution of di-nitrogen fixation by pea to the productivity and N budget of a wheat-based cropping system J. Agric. Sci, Camb., 142: 629-637.

Stevenson, F.C. and C. van Kessel. 1996. The nitrogen and non-nitrogen rotation benefits of pea to succeeding crops. Can. J. Plant Sci., 735-745.

Suwanarit, A., C. Suwamarat and S. Chotechaungmanirat. 1986. Quantities of fixed N and effects of grain legumes on following maize, and N and P status of soil as indicated by isotopes. Plant Soil, 93: 249-258.

Tobita, S., O. Ito, R. Matsunaga, T.P. Rao, T.J. Rego, C. Johansen and T. Yoneyama. 1994. Field evaluation of nitrogen fixation and use of nitrogen fertilizer by sorghum/pigeonpea intercropping on an Alfisol in the Indian Semi-Arid Tropics. Biol. Fertil. Soils, 17: 241-248.

Toomsan, B., J.F. McDonagh, V. Limpinuntana and K.E. Giller. 1995. Nitrogen fixation by groundnut and soybean and residual nitrogen benefits to rice in farmers' fields in Northeast Thailand. Plant Soil, 175: 45-56.

Toomsan, B., G. Cadisch, M. Srichantawong, C. Tongsodsaeng, K.E. Giller and V. Limpinuntana 2000. Biological N_2 fixation and residual N benefit of pre-rice leguminous crops and green manures. Netherlands J. Agril. Sci., 48: 19-29.

Turpin, J.E., D.F. Herridge and M.J. Robertson. 2002. Nitrogen fixation and soil nitrate interactions in field-grown chickpea (*Cicer arietinum*) and fababean (*Vicia faba*). Aust. J. Agric. Res., 53: 599-608.

Unkovich, M.J. and Pate, J.S. 2000. An appraisal of recent field measurements of symbiotic N_2 fixation by annual legumes. Field Crops Res., 65: 211-228.

Unkovich, M.J., J.S. Pate, E.L. Armstrong and P. Sanford. 1995. Nitrogen economy of annual crop and pasture legumes in southwest Australia. Soil Biol. Biochem., 27: 585-588.

Van Kessel, C. and J.P. Roskoski, 1988. Row spacing effects on N_2 fixation, N-yield and soil N uptake of intercropped cowpea and maize. Plant Soil, 111: 17-23.

Walsh, M., K.H.M. Siddique, A.Hashem and M. Seymour. 2004. Weed management in grain legume crops in western Australia. J. Lentil Res., 1: 37-42.

Walton, G.H. and T.R. Trent. 1988. Evaluation of pulses and other seed legumes for crop rotations in Western Australia. Tech. Bull. No. 79. Western Australian Dept. of Agriculture, South Perth, Australia.

Wani, S.P., W.B. McGill and J.A.Robertson. 1991a. Soil N dynamics and N yield of barley grown on Breton loam using N from biological fixation or fertilizer. Biol. Fertil. Soils, 12: 10-18.

Wani, S.P., W.B. McGill and J.P. Tewari. 1991b. Mycorrhizal and common root infection, and nutrient accumulation in barley grown on Breton loam using N from biological fixation or fertilizer. Biol. Fertil. Soils., 12: 46-54.

Wani, S.P., T.J. Rego and J.V.D.K. Kumar Rao. 1994. Contribution of legumes in cropping systems: A long-term perspective. p. 84-90. *In* O.P. Rupela *et al.* (ed.). Linking Biological Nitrogen Fixation Research in Asia: Report of a Meeting of the Asia Working Group on Biological Nitrogen Fixation in Legumes. ICRISAT, Patancheru, Andhra Pradesh, India.

Wani, S.P., O.P. Rupela and K.K. Lee. 1995. Sustainable agriculture in the semi-arid tropics through biological nitrogen fixation in grain legumes. Plant Soil, 174: 29-49.

Wani, S.P., T.J. Rego, O. Ito and K.K. Lee. 1996. Nitrogen budget in soil under different cropping systems. p. 481-492. *In* O. Ito *et al.* (ed.). Dynamics of Roots and Nitrogen in Cropping Systems of Semi-Arid Tropics: Japan International Research Center for Agricultural Sciences, Ohwashi, Tsukuba, Japan

Wani, S.P., P. Pathak, L.S. Jangawad, H. Eswaran and P. Singh. 2003. Improved management of Vertisols in the semiarid tropics for increased productivity and soil carbon sequestration. Soil Use and Mgmt., 19: 217-222.

Welch, R.M. 2004. Link between the application of micronutrients to crops and human health. *In* Proc. IFA International Symposium on Micronutrients 23-25 February 2004, New Delhi, India.

White, K.D. 1970. Fallowing, crop rotation and crop yields in Roman times. Agric. Hist., 44: 281-290.

Witcombe, J.R., K.D. Joshi, S. Gyawali, A.M. Musa, C. Johansen, D.S. Virk and B.R. Sthapit. 2005. Participatory plant breeding is better described as highly client-oriented plant breeding. I. Four indicators of client-orientation in plant breeding. Exp. Agric., 41: 1-21.

Worsham, A.D. and R.H. White. 1987. Legume effects on weed control in conservation tillage. p. 113-118. *In* J.F. Power (ed.). Role of legumes in conservation tillage systems. Soil conservation Society of America, Ankeny, Iowa, USA.

Wouterlood, M., G.R. Cawthray, S. Turner, H. Lambers and E.J. Veneklaas. 2004. Rhizosphere carboxylate concentrations of chickpea are affected by genotype and soil type. Plant Soil, 261: 1-10.

Zang, H., M. Pala, T. Oweis and H. Harris. 2000. Water use and water-use efficiency of chickpea and lentil in a Mediterranean environment. Aust. J. Agric. Res., 51: 294-304.

Zentner, R.P., D.D. Wall, C.N. Nagy, E.G. Smith, D.L. Young, P.R. Miller, C.A. Campbell, B.G. McConkey, S.A. Brandt, G.P. Lafond, A.M. Johnston and D.A. Derksen. 2002. Economics of crop diversification and soil tillage opportunities in the Canadian prairies. Agron. J., 94: 216-230.

Zentner, R.P., G.P. Lafond, D.A. Derksen, C.N. Nagy, D.D. Wall and W.E. May. 2004. Effects of tillage method and crop rotation on non-renewable energy use efficiency for a thin Black Chernozem in the Canadian Prairies. Soil Till. Res., 77: 125-136.