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Establishment of Legumes Following Rice - A Review

International Crops Research Institute for the Semi-Arid Tropics

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Abstract

Legumes are important food crops and a major component of rice-based cropping systems (RBCS) in many Asian countries. Crop establishment following rice is an important constraint to production and is profoundly affected by soil physical, chemical, and biological factors, and by soil management. Considerable research has been done to understand the role of these factors on crop establishment. This review evaluates these studies and investigates future research needs, which include: classification of post-rice environments in terms of suitability for legumes; breeding programs specific to legume improvement for post-rice environments; seed characteristics allowing germination in still-saturated and compact soils; enhancing germination and seedling vigor; and development of appropriate implements for tillage and sowing in post-rice soils.

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Contents

1. Introduction

Rice (*Oryza sativa* L.)-based cropping systems (RBCS) predominate in many Asian countries and in many cases include legumes as a component of the cropping system (Table 1). Although RBCS are prevalent in other regions of the world, this paper concentrates and emphasizes on Asian RBCS. The area of legumes under RBCS varies between different Asian countries but overall substantial area exists (Table 2).

A common feature of RBCS is, that the puddled soils retain a significant amount of profile available water following rice harvest (So and Woodhead 1987). Upland crops can exploit this soil moisture following harvest of rice (Cook et al. 1995). Legumes are preferred as post-rice crops, because of generally low water and other input requirements, in comparison to such crops as wheat (*Triticum aestivum* L.) for example.

Legumes are among the major food crops in Asia, both for human consumption as well as animal feed. Food legumes considered important in RBCS in Asia include soybean (*Glycine max* [L.] Merr.), mung bean (*Vigna radiata* [L.] Wilczek), groundnut (*Arachis hypogaea* [L.]), cowpea (*Vigna unguiculata* [L.] Walp.), chickpea (*Cicer arietinum* [L.]), lentil (*Lens culinaris* Medic.), black gram (*Vigna mungo* [L.] Hepper), khesari or lathyrus (*Lathyrus sativus* [L.]), faba bean (*Vicia faba* [L.]), horse gram (*Dolichos biflorus* Roxb.), and pea (*Pisum sativum* [L.]). Expansion of production of these crops is a high priority for many Asian countries (So and Woodhead 1987; Faris et al. 1992). Legumes also play a major role in maintaining and sustaining soil fertility (Rego et al. 1998). Dryland crops can be successfully grown after rice provided the crop can be established quickly and the roots can penetrate into the subsoil (Angus et al. 1983; Klodpeng and Morris 1984). However, the productivity of these crops after rice depends largely on successful crop establishment and utilization of the residual soil water (Zandstra 1982).

Growing legumes after rice presents some formidable difficulties. Based on a discussion at a meeting of senior scientists from Asian countries, major constraints to legume production in RBCS in Asia were prioritized by Faris et al. (1992) as:

Table 1 . Rice-based Cropping Systems in Asia.

Country	Cropping systems
Bangladesh	Aus rice/jute-fallow-legume Aman rice-legumes Aman rice-wheat Legumes-aman rice-legume (upland)
China	
Central China	Groundnut-rice Rice-groundnut/soybean Groundnut-wheat or rape seed; soybean-rice in second year
Southern China	Groundnut-rice-soybean-rapeseed, faba bean, pea, or sweet potato Rice-groundnut-wheat or sweet potato Soybean-rice seedlings-groundnut
India	
Northern India	Rice-wheat
Eastern & peninsular India	Rice-chickpea/grass pea/lentil/pea Rice-rice
South-eastern coastal regions	Rice-mung bean/black gram Rice-rice
Indonesia	Rice-rice-groundnut Rice-groundnut-groundnut Rice-soybean-groundnut or groundnut + maize
Myanmar	Rice-legume (chickpea, lentil, groundnut) Legume-rice-legume Sesame-rice-legume
Nepal	Rice-legume (chickpea, lentil, grass pea)-fallow Rice-legume-early rice Rice-wheat-mung bean Rice-fallow-groundnut (spring)

Country	Cropping systems
Pakistan	
Sindh	Rice-wheat
	Rice-chickpea
Baluchistan	Rice-chickpea/grass pea
	Rice-flax-coriander/pea
Punjab	Rice-wheat
	Rice-chickpea/lentil/pea/berseem clover
Philippines	Rice-mung bean/groundnut/soybean
	Rice-tobacco/vegetables
Sri Lanka	Rice-other field crops
	Rice-legume
	Rice-vegetables (onion, chillies, etc.)
	Rice-legume-other field crops
Thailand	Sesame/mung bean/groundnut/soybean/ jute-rice
	Rice-mung bean/black gram/groundnut

1. Source: Faris et al. (1992).
2. Legume includes chickpea, lentil, grasspea, and field pea.
3. 'Aus' rice is sown early in the rainy season; `Aman' is rice sown after beginning of the main rainy season.

Table 2. Area of legumes under rice-based cropping systems (RBCS) in Asia.

Country	Total area of legumes ('000 ha)[a]	Area of legumes in RBCS ('000 ha)
Bangladesh	785	750
China	13700	1300
India	18790	1990
Indonesia	NA[c]	34%[d]
Myanmar[b]	1195	141
Nepal	253	197
Pakistan	1576	262
Sri Lanka	92	NA
Thailand	1148	400

a = Area in RBCS and non-RBCS; b = Area of chickpea, pigeonpea, and groundnut only
c = NA = Data not available; d = Percentage of total area
Source: Faris et al. (1992).

- lack of adapted high yielding varieties with resistance to relevant biotic and abiotic stresses;
- pest and disease problems during crop growth and lack of reliable means for their management;
- poor crop establishment and stand development;
- problems with water that range from poor drainage and water logging in low-lying areas to drought stress especially at grain filling;
- damage due to rodents and birds;
- low temperatures during early growth in the case of winter-legumes in the subtropics;
- tillage constraints and adverse soil physical and chemical properties;
- an overall lack of appropriate management technology;
- non-availability of proper agricultural equipment for legumes cultivation;
- inadequate marketing facilities and price structure for legumes;
- lack of timely availability of inputs and credit to farmers;
- shortage of labor at critical time of field operations.

Pandey (1984) also emphasized that minimal use of fertilizer and other management inputs, poor seed quality, and near certainty of drought conditions during the reproductive period are also responsible for low yields of food legumes grown after rice.

Crop establishment and stand development rank as major determinants of legume production in RBCS. Considerable research has been done in the past on establishment of upland crops after rice and the findings are summarized and reviewed here. This information is then used to identify knowledge gaps and set future research priorities.

2. Soil physical and chemical factors affecting crop establishment

The soil physical constraints following harvest of rice usually present a hostile environment for legume germination and establishment (Cook et al. 1995). Drying of the surface soil and hardening and compaction of the plough pan layers constrain seed germination and seedling

establishment (Ramakrishna et al. 1992). Adverse soil physical conditions also limit subsequent root growth and the supply of air, water and nutrients to roots. Significant changes in soil reaction and nutrient availability (particularly phosphorus, iron, manganese, and zinc) can also occur.

Soil physical factors that affect seed germination, seedling emergence and crop establishment are soil structure, soil water deficit, aeration, temperature, and mechanical impedance of the seed zone (Larson 1964; Wanjura et al. 1970; Lindstrom et al. 1976; Schneider and Gupta 1985; Bouaziz and Bruckler 1989; Cook et al. 1995; Nasr and Selles 1995). Their effect on establishment of legumes after rice is discussed below.

2.1 Soil structure

Cultivation of rice in puddled soil conditions results in a massive structureless top soil, underlain by a plough-pan or compaction layer, generally between 15 and 25 cm depth (Cass et al. 1994). This is deliberately created for rice cultivation to limit percolation and produces changes such as reduced drainage, lower air-filled porosity and higher soil strength (Prihar et al. 1985). Puddling eliminates most pores larger than 30 µm in favor of pores less than 0.6 µm and may reduce soil water holding capacity (Sharma and De Datta 1985; Letey 1985). A decrease in specific volume of soil clods and water availability following the cultivation of wet soil is well correlated with decreased growth of upland crops (McGarry 1987; McGarry and Daniells 1987).

The structure of the surface soil altered by puddling does not present a suitable medium for the establishment and growth of legumes or other upland crops that seek to exploit the plentiful water remaining in the subsoil after rice harvest. The poor soil physical conditions for crop establishment and the significant resistance offered by the plough pan to root penetration and subsequent crop growth limit yield of legumes grown after rice (Greenland 1985; So and Woodhead 1987).

2.2 Soil water deficit

It is well recognized that optimum soil moisture content in the seedbed (surface soil) is critical for seed germination, crop establishment and initial crop growth. Soil, climate and agronomic management practices have pronounced effects on the available soil moisture content in the seedbed.

Evaporation potential varies with the location and the time of the year when a crop is sown. Legumes after rice are generally sown after the end of rainy season and during winter. In coastal Andhra Pradesh, India, black gram is relay-sown in late November and early December into the standing rice crop, just prior to its harvest. At this time potential rate of evaporation is low (<4 mm day^{-1}) and more or less constant as there is normally very little rainfall. When potential evaporation rates are stable, as in this case, soil moisture content is known to decrease as a function of the square root of time since the last rainfall event (Monteith 1991).

Tillage to prepare a seedbed accelerates soil moisture loss. A delay in sowing of legumes after tillage, will therefore, result in poor plant stand establishment. In general, legume crops that cannot be relay-sown with paddy will have a very limited optimum period of sowing for successful crop establishment. This is because germinating seeds must absorb water and reach their critical water content for germination before the effect of soil drying precludes their further development (Hadas 1985). The rate of water absorption is dependent on the water potential of a given soil, the seed-soil contact area, and the hydraulic conductivity of soil and seed.

Deep sowing (15-20 cm below surface soil) places seeds in soil with adequate soil moisture content for germination, but delays emergence of the shoot above the soil surface (Mohamed et al. 1989). This is a relevant practise for legume crops being able to emerge from deeper soil layers, chickpea being an example.

In chickpea sown on a dry seedbed in a Vertisol field, very few seedlings emerged when soil moisture content fell below 20% (W/W); the soil had a field capacity of 34% (Saxena 1987). Effects of delay in time of sowing in mung bean were studied in soil puddled previously to grow paddy (Cook et al. 1995). Sowing was done manually at 3, 5, 7, 10 and

14 days after drainage (DAD) and measurements of water potential, soil water content and emergence were made. Soil water potential at 5 cm depth was –0.01 Mpa at 3 and 5 DAD, and –0.05 Mpa at 7 DAD, and emergence was 90 ± 2%. At 10 DAD, soil water potential was –0.8 MPa and emergence was 10%, and at 14 DAD it was –1.2 Mpa and emergence was only 1%. Other laboratory studies showed that the limiting soil water potential for mung bean was –2.2 Mpa, below which germination would not occur (Cook et al., 1995). For groundnut sown in an Alfisol with bulk density in the range of 1.45-1.65 Mg m^{-3}, germination decreased when the matric potential fell below –0.05 Mpa and did not occur at a matric potential less than -0.22 Mpa (Nivedita 1992). Seeds sown in dry soil remain viable, but partially hydrated seeds in a warm seedbed can rapidly lose viability (Ellis and Roberts 1980).

Low soil moisture content may reduce overall utilization of seed reserves and also the efficiency of its utilization. With successful germination, seedlings emerge and begin photosynthesis before the seed reserves are depleted. However, if any external factor interferes with utilization of seed reserves the number of plants that are established would be affected (Hadas 1985).

Lack of adequate soil moisture predisposes seeds to damage by pathogenic organisms (Hadas and Russo 1974). It also affects the ability of seedlings to withstand other soil physical stresses, e.g. soil compaction and soil resistance (Hanks and Thorp 1956; Stout et al. 1961). In groundnut sown in soil with a low bulk density (1.45 Mg m^{-3}) all seeds that germinated emerged from the soil as well. At higher bulk densities (1.65 Mg m^{-3}) only a fraction of seeds that germinated also emerged from soil (Nivedita 1992). Bulk densities of this magnitude are known to occur in rice fallows, implying that it is not only failure to germinate but inability to emerge that could be an important factor in poor crop establishment.

Root growth of the seedlings is dependent on temperature, specific root mass, and amount of assimilates allocated to roots (Squire 1990). If the roots of seedlings are trapped in drying soil of high strength, then seedlings will be subjected to desiccation even though adequate soil moisture may be available at greater depths. To our knowledge, such desiccating seedlings of legumes in rice fallows have not been reported so far.

Differences between crop species and genotypes within a crop species in their ability to germinate and establish good plant stands from below optimal seed moisture content are known to exist. These differences may be useful in selecting legume crop species which are likely to be better adapted to sub-optimal soil moisture conditions. However, the genotypic differences found within chickpea for this trait were very narrow and unlikely to be useful because the soil moisture in the seedbed fluctuates considerably over both space and time (ICRISAT 1987).

2.3 Excess water and aeration

Poor germination in soils at or near saturation has been related to limited oxygen diffusion through thick water films surrounding the seed (Richard and Guerif 1988). The availability of water must be balanced with aeration potential to meet requirements for germination and crop establishment (Dasberg and Mendel 1971). Interactions between high soil temperature and excessive water content can promote fungal attack on the seed (So and Woodhead 1987).

Groundnut, pigeonpea and soybean are particularly sensitive to excessive moisture during germination. Mung bean emergence in the field decreased from 84 to 71% as soil matric potential decreased from -18 to -35 kPa (Cook et al. 1995).

Poor aeration adversely affects root growth also. Root growth declines as soil oxygen depletes because of reduced cell division and expansion. In addition, the permeability of the roots to water is reduced at low oxygen levels, and eventually the roots lose their ability to control water movement (Braunack and Dexter 1989). At a bulk density of 1.3 Mg m^{-3}, the soil did not impede root growth until the oxygen concentration decreased from 21% to 5%. At a bulk density of 1.5 Mg m^{-3}, root growth began to decrease when oxygen levels were reduced to 10%, and root penetration decreased sharply at lower oxygen levels. At bulk densities of $\geq$1.6 Mg m^{-3}, root penetration was greatly reduced mainly due to high mechanical impedance values (Tackett and Pearson 1964). These results showed that at moderate bulk densities (i.e., 1.5-1.6 Mg m^{-3}) root penetration of soil could be slowed when oxygen concentration of soil decreased to less than 10%. This appears to be largely an indirect effect due to limited pore space. However, at the higher bulk densities, mechanical impedance appeared to be the dominant factor affecting root growth.

2.4 Mechanical impedance

Soil puddling enhances soil bulk density and thus the pressure of seedlings must exert to penetrate the soil. High soil strength and low moisture content appear to be the major soil physical constraints limiting mung bean seedling emergence in clay soils. Cook et al. (1995) showed that maximum seedling emergence in mung bean occurred when soil resistance to seedling emergence was lowest.

The mechanical impedance of the drying puddled soil may prevent root growth (Vepraskas 1988). There are some differences among species, but root growth rates decrease sharply for mechanical impedance values of 1 and 3 MPa (Taylor and Ratliff 1969; Taylor and Gardner 1963; Taylor et al. 1966). Root growth rates are very low for mechanical impedance values greater than 3 MPa (Grimes et al. 1975; Ide et al. 1984; Vepraskas and Wagger 1989). The relationship between root abundance and mechanical impedance was approximately linear, with few roots present when the mean mechanical impedance was greater than 3 MPa.

Bulk density values are used to estimate mechanical impedance values likely to retard root growth. Root-limiting bulk density values vary with soil textural class and increase as sand percentage increases (Jones 1983; Vepraskas 1988). The root-limiting bulk densities for the clay, clay loam, sandy loam, and loamy sand textural classes were approximately 1.40, 1.50, 1.65, and 1.75 Mg m^{-3}, respectively. The root-limiting bulk densities for the loamy sand and sandy loam textural classes correspond closely to the bulk densities of root-limiting tillage pans in Typic and Arenic Paleudults that had mechanical impedance values of >3 MPa (Vepraskas 1994).

2.5. Temperature

Temperature is one of the major climatic variables affecting germination and crop establishment. Angus et al. (1981) conducted a field study at a number of locations and calculated the base temperature and thermal time for emergence. Minimum temperature for germination and degree days to germination of selected legume species are shown in Table 3. The base temperature for temperate legumes is low (0-2 ^{o}C) compared to that of tropical legumes (9-11 ^{o}C). These cardinal temperatures can be used to calculate the thermal time for given events to occur, such as germination, emergence, leaf appearance, panicle initiation, and maturity (Squire 1990). Base temperature values for pigeonpea and groundnut appear greater than values calculated from germination and flowering studies (Odongo et al. 1991; Mohamed et al. 1989; Omanga et al. 1995; Leong and Ong 1983). Over estimation of the base temperature can occur if data are included where cool nights cause chilling. Thermal time for emergence was higher in temperate legumes than in tropical legumes (Table 3).

Table 3. Base temperature and thermal time for emergence of selected legumes sown at different locations in the field.

Common name	Scientific name	Base temperature (^{o}C)	Thermal time (degree days)[a]
Temperate legumes			
Field pea	*Pisum sativum*	1.4	110.3
Lentil	*Lens culinaris*	1.4	90.1
Chickpea[b]	*Cicer arietinum*	0	NA[c]
Lupin[b]	*Lupinus* sp.	0	NA
Tropical legumes			
Soybean	*Glycine max*	9.9	70.5
Cowpea	*Vigna unguiculata*	11.0	43.0
Navy bean	*Phaseolus vulgaris*	10.6	52.1
Mung bean	*Vigna radiata*	10.8	49.6
Adzuki bean	*Phaseolus angularis*	9.9	69.9
Lablab	*Lablab purpureus*	9.6	56.2
Pigeonpea	*Cajanus cajan*	12.8	58.2
Groundnut	*Arachis hypogaea*	13.3	76.3

a) Thermal time for 50% emergence;
b) Data estimated by eye from the information presented
c) NA = Data not available
Source: Angus et al. (1981).

Other studies report substantial variation within both tropical and temperate crops in the minimal temperatures for germination, with soybean and faba bean values particularly low (Table 4). Ceiling temperatures were variable due to the different approaches used, but tropical crops in most cases had higher ceiling temperatures than temperate crops.

Table 4. The cardinal temperatures for time to 50% germination of selected legumes calculated from laboratory studies conducted under conditions of constant temperature.

	Temperatures (^oC)			
Crop	Base	Optimum	Ceiling	Reference
Tropical legumes				
Lentil	2.5	24.2	33.1	Covell et al. 1986
Chickpea	0.0	32.4	54.4	Covell et al. 1986
Faba bean	-5.8	23.3	38.0	Ellis et al.1987
Tropical legumes				
Soybean	4.0	34.3	51.0	Covell et al. 1986
Cowpea	8.5	34.5	>50	Covell et al. 1986
Pigeonpea	9.9	32.0	45.0	Odongo et al. 1991
Groundnut	10.0	34.0	44.0	Mohamed et al 1989

In the lowland rice-based systems on the east coast of India, the average maximum and minimum air temperatures during December vary with latitude (Fig. 1). This variation has implications for establishment of legumes in rice- fallows. For example, at the lower latitudes, a tropical legume such as mung bean can emerge faster, while at the higher latitudes temperate legumes such as lentil would have a distinct advantage in time taken to 50% emergence (Fig. 2). It can be expected that in rice-fallows, a high soil strength could further increase thermal time required to reach the surface. Time to emergence is important, as seedlings that emerge faster encounter a soil surface that has a higher moisture content and thus, a lower mechanical impedance.

2.6 Soil chemical constraints

Previous research on soil chemical constraints limiting grain legumes production in rice fallows was mainly concentrated on growth and development of legumes. There is little

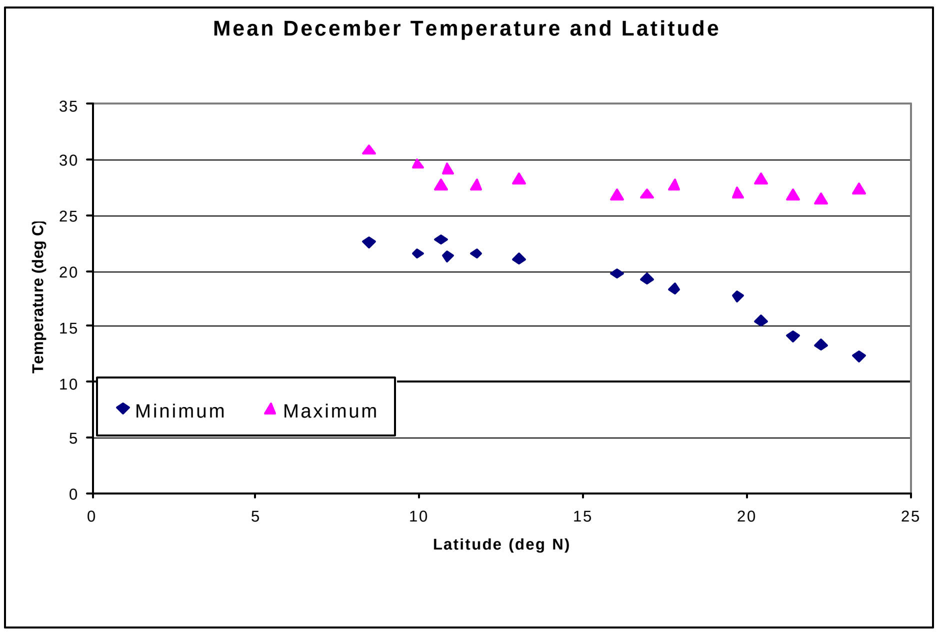

Figure 1. Relationship between mean December temperature and latitude for 14 locations on the east coast of India (Indian Meteorological Department, 1931-1960).

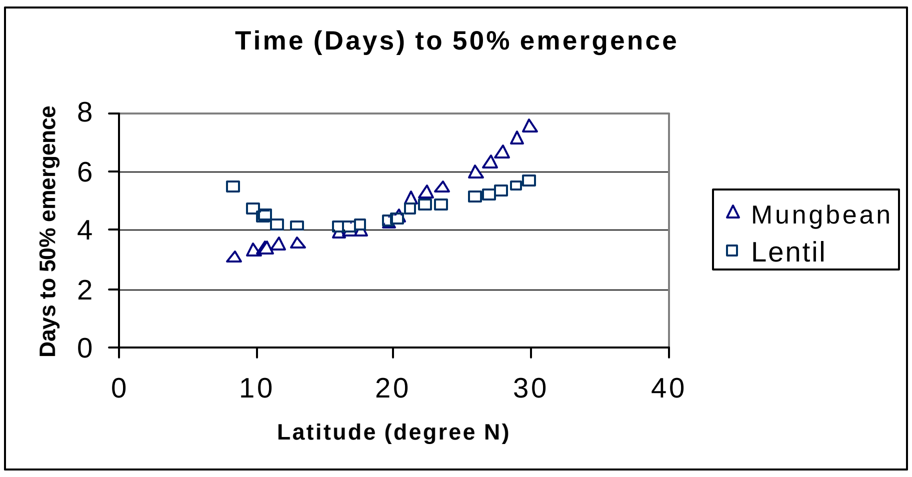

Figure 2. Calculated time to 50% emergence of crops sown at locations in India with differing latitudes.

information about the effect of chemical constraints on germination, emergence and crop establishment of grain legumes in rice fallows. Broadly, these chemical constraints can be grouped under soil salinity/alkalinity, soil acidity and nutrient deficiency and toxicity.

2.6.1 Soil salinity/alkalinity

The total rice area affected by salinity in South and Southeast Asia is 49.4 m ha (De Datta 1981), of which India has 23.2 m ha followed by Indonesia (13.2 m ha). Another 12.4 m ha of rice growing area is on alkali soils, of which Pakistan has the largest area (9.4 m ha) followed by India (2.5 m ha). Rice is a relatively salt tolerant crop and can produce in saline soils. Lowland rainfed or irrigated rice-growing conditions tend to reduce the severity of salinity by reducing salt concentration in the rice rhizosphere. However, even good rice soils are becoming saline due to either a rise in water table or the continuous use of poor quality irrigation water. When these soils are cropped with upland crops following rice, many will face salinity problems.

Most of the legumes grown after rice are sensitive to high sodicity and high salt concentration (Table 5). The harmful effects of salinity on plant growth have been well researched (Noble and Rogers 1993). Legume species vary from extremely sensitive to moderately tolerant (Lauchli 1984). Legume species sensitive to salinity suffer from poor seedling establishment and yield losses at electrical conductivities (EC_e) of less than 2 dSm^{-1} (Maas and Hoffman 1977). Lauchli and Wieneke (1979) observed that a concentration of 10 m M NaCl inhibits the growth of salt sensitive soybean varieties. Higher salt concentrations of 60 and 80 mM NaCl also reduced the growth of *Phaseolus vulgaris* (Ayers and Eberhard 1960) and mung bean (Hafeez et al. 1988).

Salinity may have adverse effects on K and Ca nutrition (Lauchli 1981) and on micronutrients. The effect of salt stress on Ca nutrition is particularly important since Ca is a key factor in the resistance of plants to salinity (LaHaye and Epstein 1969) and in the maintenance of K transport in presence of Na (Lauchli and Epstein 1979). Obviously these nutrient interactions can control the response of legumes to salinity.

Several attempts have been directed at minimizing or limiting salinity effects on plants by supplementary N application (Lips et al. 1990). However, such studies are quite rare for legumes, since these plants can assimilate N_2 as well as combined N. Inhibition of nodulation and N_2 fixation by NaCl in legumes has been studied (Wilson 1970). Wilson and Norris (1970) observed that NaCl was more detrimental to *Rhizobium*-inoculated N_2-fixing plants of *Glycine javanica* than plants receiving fertilizer N. In mung bean, salt stress inhibited nodule initiation and N_2 fixation (Balasubrahmanian and Sinha 1976). Lauter et al. (1981) found that salt stress delayed nodulation and reduced N_2 fixation in the chickpea-*Rhizobium* symbiosis. They also observed that retardation of growth as a result of salt stress was much higher in plants depending on symbiotic N_2 fixation than in plants receiving fertilizer N.

Table 5. Crop groups based on response to salt stress.

Sensitive groups		Tolerant groups	
Highly sensitive	Medium sensitive	Medium tolerant	Highly tolerant
Lentil	Cowpea	Wheat	Barley
Black gram	Fababean	Rice (direct sown)	Rice (transplanted)
Chickpea	Vetch	Alfalfa	Sugarbeet
Beans		Sesbania	Tobacco
Peas	Berseem		Karnal grass

Source: Singh (1994).

Qadar (1994) reported from a laboratory study on chickpea cultiver BG 203 that the absorption of water and root and shoot biomass were adversely affected with an increase in salinity over the EC range of 1.5 to 7.5 dSm^{-1} and this resulted in death of young seedlings.

2.6.2 *Soil acidity*

Soils of the humid tropics are generally acid. In south and southeast Asia, there is a particular problem of acid sulphate soils in which 5.4 m ha of rice grows (De Datta 1981). Some 2.0 m ha are in Indonesia, 1.0 m ha in Vietnam and the rest in other countries. Rice is also able to produce in acid soils as it does in saline soils. The pH of these acid soils rises with flooding and approaches neutrality. However, when legumes are grown following rice, soil acidity may affect these crops. In severe acid conditions (pH <4) aluminium (Al) toxicity reduces the root and shoot growth, nodulation and N_2 fixation (Chong et al. 1987). But even under moderately acid conditions (pH 4 to 6) soil acidity can affect nodulation and N_2 fixation. As pH increases with lime ($CaCO_3$) treatments, shoot and root growth, nodulation and N_2 fixation improve (Chong et al. 1987). Maximum groundnut root growth occurred at pH 7.3. Shoot growth, nodulation and N_2 fixation of peanut and cowpea were best at pH 5.9-6.3. Shoot and root growth of groundnut was relatively higher than that of cowpea at pH 3.8. Shoot and root growth of mung bean and pigeonpea (*Cajanus cajan* (L.) Millsp.) were less than that of groundnut and cowpea at pH 3.9. At this pH level, nodulation and N_2 fixation were higher in cowpea than in groundnut and other legumes. Cowpea and groundnut therefore appear to be more suitable in acid soils following rice as compared to mung bean and pigeonpea.

2.6.3 *Nutrient deficiency/toxicity*

Nitrogen deficiency is an important limitation to crop establishment in rice fallows in many countries. After a rice crop, soils are usually devoid of mineral N. A small quantity of available soil N or applied fertilizer N may help to establish a good crop stand through an enhanced root system, which also provides increased root surface area for *Rhizobium* infection. In the irrigated and lowland rice areas of coastal India, application of 20-40 kg N ha^{-1} to the following legume crops (such as mung bean and black gram) is a common practice. Addition of nitrate at an early growth stage can also reduce Cl^- uptake and toxicity in soybean (Weigel et al. 1973). Once nodulation and N_2 fixation starts, the need for soil-derived or fertilizer N diminishes. Due to mineral reserves in legume seeds, deficiencies of other nutrients may not arise at the seedling establishment stage, if the top soil has enough moisture.

3. Biological factors affecting crop establishment

3.1. Seed

3.1.1. Seed quality

Crop establishment is affected to a considerable extent by the quality of seed. Viability of legume seed is more sensitive to environmental factors than seeds of cereals. A number of pre-harvest and post-harvest factors contribute to loss in seed quality, which is expressed in terms of poor emergence in the subsequent crop.

Seed is vulnerable to damage by weather conditions and also to insect and disease attack at the time of physiological maturity. Susceptibility to weather damage is due to absence of hard-seededness (Kilen and Hartwig 1978). Mung bean and short-duration pigeonpea suffer relatively more damage due to unfavourable weather. On the other hand, hard-seededness may be disadvantageous unless it can be readily broken either by abrasive or heat scarification treatment, although it decreases progressively during storage. Failure to break hard-seededness may result in poor or uneven germination.

In areas where rainfall and/or high humidity coincide with the seed ripening phase, it increases seed respiration and decreases stored assimilates in cotyledons leading to poor quality seed with low vigor (Howell et al. 1959). Alternate wetting and drying associated with intermittent rainfall causes rupture of cell membranes, resulting in cracking of cotyledons and seed coat and prolonged respiration. High temperature during maturation can also have an adverse affect on seed germinability and emergence of soybean (Green et al. 1965).

Harvest of immature seeds causes rapid seed deterioration during storage due to fungal attack leading to reduced seed viability, poor germination and low vigor (Mugnisjah and Nakamura 1984). A delay in harvest beyond physiological maturity of seed exposes legume crops to unfavorable climatic conditions and results in poor seed quality (Mugnisjah and Nakamura 1984).

Harvest and post-harvest handling processes affect seed quality considerably (Heslehurst et al. 1987). During storage, initial seed quality, hygiene and protection and storage environments affect final seed quality. Insects such as bruchids (*Callosobruchus* spp.) can severely damage legume seeds during storage (Campbell and Reed 1987). Similarly, storage environment can affect viability. A rise or fall of 1% moisture and 5^0 C temperature can halve or double the viability period of seed (Harrington 1963).

In most Asian countries, the legume seed which farmers buy from local merchants is not only poor in viability but also in purity. Certified seed of most legumes is generally not available.

3.1.2. Seed Germination

Apart from good seed quality, viability and dormancy could affect establishment of legumes in rice fallows. Seed dormancy may be because of hard-seededness. Many legumes exhibit dormancy which may be advantageous or otherwise. Substantial dormancy has been found in Virginia types of groundnut.

Type of germination also influences establishment of legumes in rice fallows. Most post-rainy season crops have hypogeal and most rainy season crops, with the exception of pigeonpea, have epigeal germination. Baldev (1988) suggested that mode of germination may have some significance for adaptation. For example, hypogeal germination may have been evolved to enable better germination of seeds that are placed deeper in moist soil when top soil is drying out. Epigeal germination would have interfered in shoot emergence. However, under conditions of plentiful moisture, cotyledons will have little difficulty in emerging from soft soil. Baldev (1988) considered epigeal germination as primitive for this reason. Hypogeal germination has an additional advantage over epigeal germination in that if the seedling is damaged by desiccation, insect attack, or animal grazing, the lateral branches develop from the cotyledonary buds in the hypocotyl region. This provides an additional chance for the seedling to establish under unfavourable conditions.

3.1.3. Seedling vigor

After seeds have germinated, seedling vigor assumes importance, especially in sowings done on hard soils that are not properly tilled. Greater seedling vigor helps in rapid establishment, canopy development for greater light interception, weed suppression and soil protection (Sivakumar and Virmani 1984). Seedling growth consists of three phases: a) heterotrophic, which includes physiological activity prior to initiating of photosynthesis; b) transition between heterotrophic to autotrophic; and c) autotrophic, with metabolic activity from energy derived from photosynthesis. Seed reserves and size of embryo meristem influence growth of seedlings and also subsequent crop growth (Whelley et al. 1966).

Large-seeded cultivars tend to produce larger and more vigorous seedlings which have an advantage in stand establishment under adverse conditions. In cowpea, germinating hypocotyl and shoot length, vigor index and dry matter were positively correlated with seed weight (Paul and Ramaswamy 1979). A study on seedling growth and seed size using 20 pigeonpea and 23 chickpea genotypes showed a positive and essentially a linear relationship with seed size in both crops until two weeks of growth (Narayanan et al. 1981). With the advancement of growth, the relationship became poor and did not result in appreciable increase in yield (Saxena et al. 1981). In soybean, however, larger seed size has been found to give vigorous seedlings and also ultimately higher yield (Smith and Camper 1975). Pigeonpea characteristically lacks seedling vigor and fast early vegetative growth until about 40-50 days after sowing. Brakke and Gardner (1987) reported that leaf area, photosynthetic activity and dry matter accumulation in pigeonpea up to 50 days after planting was less than half of that of soybean or cowpea. They considered that low accumulation of dry matter was due to its small seeds and rejected the view that the slow growth of pigeonpea seedlings was due to greater partitioning of dry matter into the roots as root growth was equally slow as shoot growth. They also suggested that genotypes with epigeal emergence may allow faster seedling growth. Hybrid pigeonpea shows greater seedling vigor as compared to varieties (Saxena et al. 1996).

3.2 Beneficial microorganisms

Successful establishment of legumes also implies establishment of a healthy N_2-fixing symbiosis, such that a major proportion of the plant's N needs can be met by biological nitrogen fixation (BNF). However, in flooded paddy situations rhizobial numbers are known to decline to levels insufficient for satisfactory nodulation (Rupela et al. 1987). Indeed, response to rhizobial inoculation can generally be found in legumes following rice (e.g., Sattar et al. 1997). Establishment of an effective symbiosis also implies that the *Rhizobium* itself has some tolerance to the potentially unfavourable soil environments near harvest time of rice. These include waterlogging (anaerobic conditions), salinity, and rapid drying of surface soil. Sustainable cropping systems are also characterized by healthy development of associations of vesicular arbuscular mycorrhiza (VAM) with at least some of the crops in the system (Thompson 1987). Decline of apparently "normal" associations of VAM leads to increased susceptibility to nutrient and water deficiencies, as VAM acts as an extended root system. Soil flooding during rice growth may at least alter the balance of VAM in the soil, compared to a virtually continuously aerobic soil. However, dynamics of VAM in RBCS have not been studied to the extent that conclusions can be drawn.

3.3. Diseases

Fusarium wilt, pre- and post-emergence damping-off, seed and seedling blight, and root and collar rots are important soilborne diseases of food legumes. These diseases tend to be more severe in RBCS than upland cropping systems. *Fusarium* wilt of chickpea and lentil are widespread in India, Nepal and Bangladesh. Seed and seedling disease are caused primarily by *Pythium* spp. and *Rhizoctonia solani*. Root rot is caused by several different soil-borne fungal pathogens including *Aphanomyces euteiches*, *Fusarium solani*, *Pythium* spp, *Thielaviopsis basicola*, and *Sclerotium* spp. Root rot severity is influenced by the amount of stress the plant is exposed to; soil compaction, poor drainage and resultant excess moisture, low soil fertility, low pH, and temperature extremes exacerbate root rot severity. *Aspergillus* spp. causes crown rot in groundnut, which affects the seedlings. Root rots and collar rots are caused by *Sclerotium rolfsii*, *Rhizoctonia bataticola* (*Macrophomina* *phaseolina*), *R. solani*, and *F. solani*. Foliar diseases caused by species of the genera *Botrytis*, *Stemphyllium*, and *Alternaria* are particularly important in RBCS when conditions favor a humid canopy microclimate.

3.4. Insect pests

Insect pests can cause substantial yield losses to legumes in rice-based cropping systems (Litsinger et al. 1978). Cut worms (*Agrotis* spp) and army worms (*Spodoptera* spp) affect plant stand. However, seedling pests are less serious than pests which attack the plant during the reproductive phase. Only infrequently is the insect damage to legume seedlings severe enough to warrant use of insecticides.

Chickpea is attacked by relatively few insect pests, possibly due to its acid exudation from leaves (Reed et al. 1987). In the seedling stage only *Helicoverpa armigera* and *Aphis craccivora* are potentially important pests (Reed et al. 1987). *H. armigera* is the most important pest of chickpea and feeds at all stages, but high eonomic losses are due to damage to pods. *A. craccivora* causes damage by sucking liquid from the phloem but cause more substantial damage as the vectors of chickpea stunt virus.

Singh and Singh (1978) listed three pests of seedling pigeonpea, *Myllocerus undecimpustulatus*, *Madurasia obscurella* and *Empoasca kerri*. Only the jassid, *E. kerri*, was considered potentially serious. A number of other beetles and hemipterans are listed as pests in the early vegetative stage by Lal et al. (1981) and Lateef and Reed (1990). As mentioned above, these early-season pests are of relatively minor importance (only 3.3% yield loss; Rangaiah and Sehgal 1984) when compared to the large yield losses caused by flower and pod feeding insects.

Important pests of groundnut seedlings include foliage feeding insects such as *Aproaerema modicella*, *Spodoptera litura* and *H. armigera*, and virus vectors including *A. craccivora* and *Thrips palmi* (Wightman et al. 1990). These would most likely be a problem in late planted crops or if early season populations are above normal. Equivalent infestations of A. modicella would cause much greater yield loss at 10 days after sowing (DAS) than at 60 DAS (Shanower et al. 1993). The yield loss due to *S. litura* attacking 10-day old seedlings was 37% compared to <18% when seedlings older than 30 days were attacked (ICRISAT 1987).

A less specific group of pests live in the soil and feed on the seed, roots and/or stem of the developing crop plants. The damage may reduce plant vigor, cause wilting or even death of the seedlings. These pests include adult and/or immature stages of termites, dermaptera, millipedes, ants, beetles, lepidoptera and orthoptera (Reed et al. 1987; Lateef and Reed 1990; Wightman and Ranga Rao 1994). Little information exists as to the impact of these pests on seedling establishment. These pests often exhibit a highly variable distribution within a field and thus their impact may be very localized. The relative importance of these pests in rice fallows as compared to adjacent upland conditions has not been systematically documented.

4. Management factors affecting crop establishment

4.1 Land preparation

After harvest of rice, the soil is often tilled with tine implements prior to sowing the second crop. The use of low energy tillage methods confine cultivation to a shallow depth, giving rise to a compacted layer which may impede the root growth of crops in clay soils (So and Woodhead 1987). Soil is usually wet after rice harvest and tillage often takes place with the soil moisture content above the plastic limit, which tends to produce an excessively cloddy surface. Tillage of the soil after the rice harvest may recreate pores larger than 30 μm in the seedbed. However, the structure of paddy soil is unstable because of mechanical shearing of aggregates during puddling. Furthermore, the previous intensive cropping decreases soil organic matter and hence the organic bonding of soil particles. Consequently the large pores formed during tillage will tend to collapse during subsequent rainfall and the soil will revert to a less favorable structural condition (Cass et al. 1994). Bulk density of a soil tilled after rice harvest increased with time, because of soil shrinkage, from an average of 0.85 Mg m^{-3} to 1.20 Mg m^{-3}, and there were few benefits from tillage on mung bean emergence (Cook 1989).

4.2 Aggregates

Cultivation of wet puddled clay soils tends to produce an excessively cloddy surface soil, and tillage of dry soil creates a higher proportion of smaller aggregates (Cook 1989). The ability to create soil aggregates of a desired size range depends on soil friability, which quantifies the inherent capability of soil aggregates to fragment into smaller units. Friability values for a silty clay loam were 0 ("not friable") at 7 days after drainage (DAD), but were 0.3 ("very friable") at 10 DAD when soil had dried beyond its liquid-limit moisture (T. Woodhead, personal communication 1994).

A cloddy seedbed often results in poor establishment due to less seed-soil contact and reduced water transmission to seeds (Larson 1964; Hadas and Russo 1974). However, the fine aggregates (<0.5 mm geometric mean diameter), after wetting and drying, tend to form a dense seedbed with high soil strength, which impedes emergence (Schneider and Gupta 1985).

Seedling emergence is related to the size and continuity of soil pores as well as to soil strength (Larson 1964). Emerging seedlings often utilize continuous soil pores and other planes of weakness (fracture planes, ped faces), thereby bypassing potentially higher impedance zones (Whiteley et al. 1981). Tillage in poorly structured soils can enhance emergence by producing aggregates and causing random fractures (Hadas et al. 1978; Hundal and De Datta 1982).

Soil aggregate size distribution controls water transmission to seeds through seed-soil contact and hydraulic conductivity of the soil (Collis-George and Hector 1966; Dasberg and Mendel 1971). Seedlings emerged more quickly from soil aggregates of 1.9 mm mean diameter than from 1.0 mm because the emerging shoots might have found easier pathways between larger than smaller aggregates. Research has shown that the optimum seedbed is composed of aggregates in the range of 1-5 mm diameter with up to 15% of finer material (<250 µm) to block larger pores (Russell 1973). In addition to this, it is important that there is adequate seed-soil contact to facilitate water movement into the seed, and that there is adequate aeration. Most commonly, adequate seed-soil contact is obtained by light packing with rollers or press-wheels. However, excessive pressure can lead to compaction of the seedbed, which may delay germination (Dexter 1988).

The rate of drying of the surface soil is an important factor in the success of the germination process. The rate is particularly high when the surface soil is excessively cloddy, such as after cultivation of a wet clay soil. Cook (1989) observed a rapid decrease in the gravimetric water content of the surface 5 cm of a tilled seedbed over time (from saturation to -1500 kPa within 7-12 days after drainage), because of the combined effects of evaporation and drainage. It was also noted that decreasing soil matric potential strongly reduced the percentage germination of mung bean. In reality, these factors strongly interact in such a way that the relative contact area decreases rapidly with increasing soil aggregate size and decreasing soil-water matric potentials.

4.3 Time of sowing

In areas with double-cropping systems, duration of the two component crops normally cover the entire growing season, leaving little room for adjusting the sowing date for growing food legumes before and/or after rice. In such cases, the sowing date of the legumes is determined by the duration of the main crop (Patanothai and Ong 1987).

In RBCS, legumes are generally not sown when it is the optimal time for their cultivation but when the opportunity exists. Date of sowing of legumes in rice fallows is determined by such factors as the date on which rice is transplanted; the duration of the rice crop; whether multiple crops of rice are taken and the lag time from harvest of the rice crop until the field is prepared for legume cultivation.

However, there are possibilities of adjustments within the limits imposed by the individual cropping systems to improve the timeliness of sowing. Some modifications in land preparation and sowing practices would be involved to coincide sowing with the appropriate soil moisture condition for good crop establishment. In some cases, there would be a need to change the variety or sowing date of the preceding rice crop so that sowing date of the following legumes could be moved forward to avoid drought stress during late growth stages. This is the case with RBCS in which early rice varieties are required if sowing time of legumes is to be optimized. These sowing date adjustments can also be enhanced by mechanization to reduce the turn-around time and speed up the sowing operation (Patanothai and Ong 1987).

Upland cropping system legumes, following the main crop, are often sown into the stubble of the preceding crop without tillage or with a minimum of disturbance. A major problem affecting the success of the follow-on crop in this system is the rapid rate of drying of the surface soil. Farmers face the dilemma that if planting is done too soon (such as before the end of the wet season) seeds may rot or be attacked by fungus and seedlings may be damaged by waterlogging. On the other hand, if planting is delayed the surface soil may dry out and germination and early growth will be retarded due to insufficient surface soil moisture (So and Woodhead 1987).

Cultivation of black gram as a relay crop following rice is a unique system in the coastal districts of Andhra Pradesh (India), which has recently expanded in area. It involves sowing of the legume by broadcasting into the standing rice crop, 2-3 days before its harvest. The legume crop grows entirely on residual moisture and fertility. The success of this legume is attributed to its capability of seeds to germinate, of seedlings to establish with high initial soil moisture (flooding), to withstand trampling during harvesting of the rice crop, and of fast initial growth habit (Satyanarayana et al. 1994).

4.4 Method of sowing

Plant population and plant spacing are affected by method of sowing and yields of legumes are related to plant population. Carangal (1985) observed that yields of soybeans after lowland rice are linearly related to plant population density in the range of 40-70 plants m^{-2}.

In Asian countries, food legumes are either sown in hills or by broadcasting, depending on specific situations. Broadcasting is the most common practice because it is fast and requires less labor. Broadcast sowing of soybean just before rice crop harvest generally results in poor plant stand (Syarifuddin and Zandstra 1978). An appropriate increase in seed rate offsets plant stand problems due to broadcast sowing. Availability of simulation models can help to approximate optimum plant populations in RBCS, which can be verified in limited field trials. Equal row spacing has long been advocated, but this takes time and labor and farmers are reluctant to adopt it. Seed drills are rarely used because appropriate low-cost machines are generally not available. Normally, sowing needs to be done within a narrow window of opportunity, forcing the farmer to use the quickest method available. In other cases labor may be a constraint, or the expected output may be too low and too risky in the farmers' view for more intensive methods to be worthwhile.

5. Alleviation of constraints to crop establishment

5.1 Tillage

Puddled soil conditions hinder germination, emergence and establishment of crops soon after paddy harvest, due to low porosity and compaction layers at shallow depths. There is scope to improve crop establishment of food legumes through various tillage and other management practices. In the upland system, the amelioration of compaction layers will be beneficial to both the legume as well as the main rice crop. But, in the lowland system the presence of these compaction layers is somewhat of a dilemma. It is a necessity for the lowland rice crop, but it is a production constraint to the upland follow-on crop (Patanothai and Ong 1987; So and Woodhead 1987).

Grain legumes are sown using any of zero, minimum or normal tillage. The most common practice in rice fallows is zero tillage for mung bean, black gram, cowpea, lathyrus, and lentil. Zero tillage significantly reduces the risk of crop failures caused by early season drought, minimizes cost of land preparation and facilitates timely sowings of several legumes. However, yield levels are normally very low due primarily to poor plant stand establishment.

Minimum tillage is practiced, especially in medium- to heavy-textured soils, in both lowland and upland rice fields. However, as this is normally done with bullock/buffalo-drawn implements, or more recently with small rotovators, tillage depth is shallow (<10 cm) and seedbed preparation is uneven. Seed is normally broadcast sown into the ploughed soil and the soil then levelled by dragging a heavy plank of wood, or suchlike, across the surface. This procedure certainly improves plant stand over zero tillage treatment but there is considerable

scope for tailoring optimum tillage practice to specific agro-environmental conditions. Improvements in this regard will depend on advances in affordable mechanization.

Resource conserving tillage (RCT) practices – specifically zero tillage, promoted by the Rice-Wheat Consortium for the Indo-Gangetic Plains (RWC) in Nepal and other countries has radically cut the cost, time, and drudgery of sowing wheat after rice, and can be used for other crops also. Tilling less (minimum tillage) not only saves costs but significantly increases crop yields in a rice-based system. Because rice is grown on puddle soils, preparing to plant subsequent crops (wheat or legumes) can normally take two weeks or more, and even require additional irrigation. Sowing wheat as soon as possible after the rice harvest in the fall, the crop matures before the hot winds of spring, which shrivel undeveloped grains (CIMMYT 2000). Similar techniques, using minimal tillage and seed drills for sowing legumes after rice are under experimentation in Nepal (Ganesh Sah, Head of the Agricultural Implements Research Center, Birganj, Nepal – personal communication).

Deep tillage is used to break strong compaction layers, preferably not over the whole field, but along parallel strips at 30-50 cm spacing. The legume crop can then be sown over the strips to encourage deeper root development and access to the subsoil water. At IRRI, Philippines high-yielding mung bean was grown successfully after lowland rice, without fertilizer or irrigation, by using a single tine to disrupt the compacted zone, and sowing seeds along the tilled strip (Maghari and Woodhead 1984). Measurements on deep-strip tillage have shown that a force of 5-7 kN is required for a single tine to shatter the soil to a depth of 35-40 cm. This force is too high for a pair of bullocks to impart. A two-wheel tractor (power tiller) can be used for deep-strip tillage but the soil conditions after rice harvest are such that traction is usually inadequate (So and Woodhead 1987).

Good land preparation facilitates crop establishment because it provides favorable conditions for seed germination, seedling emergence and subsequent crop growth. Work at IRRI on soybean establishment under rainfed conditions has shown that drainage a day before rice harvest followed by one tillage with a rotovator gives the best soybean yield

(Syarifuddin and Zandstra 1978). Timing of tillage after harvest of paddy influences the seedbed quality greatly. Tillage of a clayey rice soil at high water contents required relatively large tillage draft forces, and resulted in a cloddy, sticky seed zone and compaction and smearing of lower layers by tillage equipment or foot traffic. The mean emergence of soybean and mung bean from such seedbeds was only 13 and 14% respectively. Tillage under dry soil conditions (14-15 days after drainage), resulted in inversion of dry surface soil into the seed zone and enhanced drying of the moist subsurface soil. Therefore, the potential benefits of reduced soil strength and a fractured soil structure were countered by lack of adequate available water for mung bean establishment (Cook et al. 1995).

Poor germination, plant stand, growth, and yield of groundnut, grown after wet season puddled rice in Andhra Pradesh (India), is attributed to inadequate seedbed preparation. Experiments showed that tillage with a rototiller gives highest emergence of groundnut. Therefore, use of rototillage was suggested for growing groundnut after puddled rice in light-textured soils (Prasadinin et al. 1993).

Land preparation takes time and labor, and in some situations needs appropriate farm equipment. Most farmers in South and Southeast Asia have only animal-drawn equipment. Low-cost small equipment makes land preparation slow and poses difficulties to farmers when land preparation needs to be done in a short period of time on heavy soils. Since preparatory tillage adds to cost of production, and because tillage effects are not consistent, proper evaluation is essential before recommending tillage practices for establishment of legumes following rice (Cook et al. 1995).

5.2 Sowing

Method of sowing plays an important role in establishment of a good plant population of legumes after rice. In a zero tillage system, seeds are broadcast either before or after harvesting rice, which results in uneven and poor plant stands because of poor seed germination. Several sowing techniques are available to improve plant stands. One such technique is to dibble the seed at the base of rice stubble. This is commonly followed in rice-soybean in Thailand and rice-rice-soybean in China, Taiwan and Indonesia (Carangal et al.

1987). Experiments have also shown that seeding in rows along with tillage, instead of broadcasting, increased mung bean yield to over 1700 kg ha^{-1}, (or four times the Philippines national average). Mung bean yield in these studies was highly correlated with emergence (IRRI, 1985, 1987). Drying top soil is a major determinant of crop establishment when seeds are sown on residual soil moisture (Lawn and Williams 1986). Deep sowing is an obvious way to reduce the effect of dry top soil. This practice has been used successfully by farmers in northeast Thailand for establishing groundnut grown after rice (Patanothai 1985).

Appropriate farm implements are critical to improve crop establishment and plant stand. Seeding implements such as a rolling injection planter and an inverted T-planter can sow legume seeds efficiently in light to medium textured soils (Carangal et al. 1987). Choudhary and Pandey (1986) reported that a multi-crop seeder (inverted-T) can be used for seeding of legumes in a range of field conditions, with minimum risk of crop establishment failure. The inverted-T seeder generally achieved maximum mung bean emergence in tilled treatments except under very wet conditions. In wet soils the seeder gave uneven seed spacing because of wheel slippage, resulting in clumping of plants. Carangal et al. (1987) reported that performance of this equipment was good only in light to medium soils but not in heavy clay soils.

The effectiveness of the manual furrow sowing and manual dibble seeding techniques were evaluated under both tilled and no-till conditions, and compared with an inverted-T seeder (Cook et al. 1995). Manual furrow sowing was more effective when the soil was relatively wetter, whereas manual dibbling was more effective when the soil was relatively drier. This was because of the greater water conservation and the absence of a hard cap which develops on closing the dibble in wet soil. In a comparison based on the cost of the seeder and labor, and the seed spacing, no-till manual furrow seeding and manual dibble sowing were found to be equally effective management options for establishment of mung bean after rice (Cook et al. 1995).

A mechanical relay seeder and manual broadcast seeding were evaluated for sowing legumes after rice harvest in Indonesia (IRRI 1987). The relay seeder gave mung bean emergence of 90±10% when seeding was done at 3 and 9 days after drainage (DAD) on a wet clay soil (soil moisture 0.55 cm^3/cm^3). But emergence from manual (dibble) seeding on those same days was only 48± 2 and 62± 2%. Higher emergence from the mechanical seeder indicates that the seed zone soil disrupted by the seeder was weaker than the soil pressed over the dibbled seeds (IRRI 1987). In another trial, mung bean and soybean were seeded 3 DAD into soil with moisture content of 0.45 cm^3/cm^3 at 5 cm depth. Emergence for mung bean was 65± 5% and 26± 5% and for soybean 34± 3% and 0% for the mechanical relay seeder and broadcast seeding, respectively. Lack of emergence of the broadcast soybean seeds was due to inadequate imbibition of seeds for germination (T. Woodhead, personal communication 1994).

The time of sowing is an important factor that determines the success of legumes grown after rice. The control of the turn-around time between rice harvest and the sowing of the follow-on legume crop is used to avoid the problem of dry hard soils. Studies at IRRI in the Philippines have shown that the optimum time for mung bean seeding was 1-8 DAD for no-till soils and 3-5 DAD for tilled soils. At more than 11 DAD, the soil water availability may be inadequate for seed germination, and soil drying makes seed zone preparation also difficult (Fyfield 1987; Cook et al. 1995).

Field experiments were conducted at IRRI to study the effects of deliberate seeding delay, and its interactions with seed zone tillage on emergence percentage for manually seeded mung bean (Cook et al. 1995). Seeding delay, measured from the time of draining the re-flooding water, extended from 1 to 15 days on non-tilled (NT) plots and from 3 to 18 days on plots that had a combination of deep strip tillage and surface tillage (ST). Emergence was similar at 90± 5%, for seedings at 1 to 5 days after drainage (DAD), for NT and ST. For delays beyond 5 DAD, emergence declined progressively to about 70% for NT at 15 DAD, and to about 40% for ST at 18 DAD. The larger decline for ST was the result of more rapid drying of tilled compared to non-tilled soil. It was observed that soil moisture at 0-5 cm correlated significantly with emergence percentage, and the optimum time for mung bean sowing was from 1 to 8 DAD for no-till, and from 3 to 5 DAD for tilled soils (Cook et al. 1995).

Seedling emergence and vigor can be hastened by soaking legume seeds in water immediately before seeding or by an overnight seed priming treatment. Field trials in a silty clay soil showed that a 2 h seed soaking of mung bean caused a 10% increase in percentage emergence over unsoaked seed sown into drier soil at 7 DAD (Woodhead 1994). Seed soaking and seed-soil contact also affected time taken for emergence. Small seeds that were soaked for 2 h emerged in 2.1±0.2 day (d) compared to 2.5±0.2 d for non-soaked seeds, but large seeds required 2.8±0.2 d irrespective of soaking. Seed priming involves placing seed in water overnight, for about 8 hr, surface drying them and sowing them on the next day (Harris et al. 1999). Substantial positive effects of seed priming of chickpea sown after rice have recently been obtained.

5.3 Seed size and vigor

To alleviate the problem of crop establishment after rice, a possible agronomic solution is to use legumes that are capable of penetrating hard soil horizons. Some species do have better ability to overcome mechanical resistance (Elkins et al. 1977). Groundnut was reported to have higher root elongation rates than pigeonpea and peas when soil mechanical resistance increased from 0 to 3 MPa (So and Woodhead 1987).

Seedling emergence and subsequent vigor is dependent on seed quality and genotype. In a growth-chamber study, larger seeds were found to have more vigorous growth than smaller seeds (Patanothai and Ong 1987). The plant height at 7 days after sowing (DAS) was higher from large seeds than from small ones (17.0±0.2 compared to 13.0±0.2 cm). In the field, plants (measured at 39 and 45 DAS) were 34±3% taller for large than for small seeds for sowing done at 4 DAD, and 18±2% taller for sowing done at 7 DAD. Total dry matter measured at 35 DAS showed similar effects : a 70±10% advantage for large seeds for sowing done at 4 DAD, and 40±20% for sowing done at 7 DAD. The greater effects for the sowing done at 4 DAD may be because larger seeds had greater reserves of energy to overcome higher soil strength for that seeding, whereas soil was wetter at 7 DAD due to rain on that day. Therefore, it can be suggested that larger seeds of a seed lot could be selected for sowing particularly in adverse seed bed conditions as usually found after rice.

5.4 Mulch and soil amendments

Effective management of surface-soil organic matter should improve the structural stability of the soil. This can be achieved through mulching, green manure crops, stubble incorporation and inter-cropping combined with a zero tillage practice. Rice-straw mulch can be used to improve emergence and early growth of post-rice mung bean. In a field trial, the mulch lessened seed zone drying during 2 to 5 days after drainage (DAD) by 0.02 units of volumetric moisture and kept the soil temperature lower by 2.5^oC. Consequently, emergence was higher from mulched than non-mulched soil by 9% (97 versus 88%) and by 17% (84 versus 67%) for sowing done at 2 and 5 DAD, respectively (So and Woodhead 1987).

The establishment of early root development in the puddled soils may be improved through soil amelioration, using Ca^{++} from sources such as gypsum ($CaSO_4$) or slaked lime ($Ca(OH)_2$). As puddling results in soil dispersion, the application of gypsum is expected to improve the physical conditions of the soil following rice. Despite considerable benefits observed on dispersive sodic soils in Australia, no beneficial effects were observed on legume yields in south-east Asia (Kirchhof and So 1995). This is probably associated with the high base saturation of the relatively young soils investigated, where exchangeable sodium levels are low. The dispersed clay particles are probably flocculated by the end of the rice season and hence the application of gypsum would not have the desired effect. It is generally observed that the application of mulch had little or no effect on yields in the wetter areas but may increase yield significantly in drier areas. Some non-sodic puddled soils can be successfully ameliorated by the addition of low concentrations of $CaCl_2$ in the first irrigation water (So and Woodhead 1987).

The problem of waterlogging of seeds or seedlings can be a serious constraint to the success of legume crops. Where the probability of excessive water during the early part of the crop is high, several methods may be considered. Firstly, the use of Ca-ameliorants to improve structure and drainage may be useful, particularly on soils dominated by exchangeable Na and/or Mg. Secondly, the use of legumes that can adapt to waterlogged conditions in a system referred to as the wet soil culture technique developed at the University of Queensland (Troedson et al. 1985). Some legumes such as soybean, green gram, and black gram are better suited to grow under high soil moisture conditions early in the season, compared to other legumes such as chickpea, peas, and lentil. The differences are due to their respective capabilities to withstand poor aeration for extended periods of time and germination habit (epigeal or hypogeal).

5.5 Enhancing beneficial microorganisms

To ensure appropriate establishment of legumes after rice, it is advisable to take steps to enhance the beneficial symbioses between the legume and microorganisms. Techniques of rhizobial inoculation are well established (e.g., Sattar et al. 1997) but rarely applied for legumes grown as subsistence crops. For overcoming specific soil chemical problems that emerging seedlings could face, along with *Rhizobium* inoculation, the seed could be pelleted with lime, rock phosphate, or trace elements known to be deficient. There is a need for much better diagnosis of BNF shortcomings in crops following rice, concerted efforts to apply known rhizobial inoculation technology, and use of legume genotypes better able to form effective symbioses (Rupela 1997). There is an urgent need for surveys to determine if populations of VAM normally forming beneficial symbioses with post-rice legumes are indeed adversely affected by flooding during rice growth. However, if this is the case, remedial measures would be difficult until viable VAM inoculation techniques for field crops are developed.

5.6 Disease control

5.6.1 Host plant resistance

Use of disease-resistant cultivars is the most economic and practical method of disease control. Work on resistance breeding in groundnut, chickpea, pigeonpea, lentil, pea and other legumes is in progress at several locations in India, Syria, Taiwan and USA. Several sources of resistance have been identified and resistance has been incorporated in high yielding wilt-resistant chickpea cultivars (ICCV 2, Avrodhi, JG 315) (Nene et al. 1989a). Through multi-location testing, ICCs 2862, 9023, 10803, 11550 and 11551 were found to be resistant to wilt and root rots in India.

Good progress has been made on the identification of resistance to *fusarium* wilt in pigeonpea. Disease sick plots are available (Nene et al. 1989b). A few resistant/moderately resistant and high yielding varieties such as NP(WR) 15, BDN-1, Mukta, C 11 and Maruti (ICP 8863) are released. Resistance to *phytophthora* blight is not available for the virulent isolate from Kanpur (India). Several lines of pigeonpea have been identified as resistant to sterility mosaic (SM) disease. Some of these are resistant to wilt also. Three lines, ICP 11302, ICP 11303 and ICP 11304, are resistant to SM, wilt and *phytophthora* blight (Nene et al. 1989b).

Little is known about the genetic resistance in groundnut to invasion by soilborne and seedborne fungi and bacteria (Middleton et al. 1994). Genetic resistance to *Aspergillus niger* and *A*. *flavus*, although identified, depends on the presence of undamaged testa (Mehan 1988). Any damage to the testa generally reduces the level of resistance. Resistant sources to other soilborne (*S. rolfsii*) and seedborne fungi and bacteria (*P. solanacearum*) have been identified. However, no high-yielding cultivar with a high degree of resistance to stem and pod rot (Brenneman et al. 1990) and bacterial wilt (Liao et al. 1990) has been released in any country.

5.6.2 Seed treatment

Soil and seed-borne diseases cause enormous loss to grain crops grown both in uplands and lowlands. Field fungi associated with grain legume seeds cause deterioration of quality, affect viability and reduce germination of seeds. More than 10 fungi causing disease were found in chickpea seeds, 5 in lentil, 17 in black gram, and 9 in lathyrus. Similarly, eleven seed-borne diseases were reported in four major pulses from Bangladesh alone (BARI 1991). These are blight, wilt, and seed rot of chickpea, rust of lentil, leaf spot and seed rot of mung bean, and seedling blight, anthracnose, foot rot, leaf spot, and seed rot of black gram.

The seed-borne disease infection can be effectively reduced if the seeds are treated with chemicals before sowing. For example, seed treatment with Benlate T-20(R) (20% Benomyl + 20% Thiram) can minimize collar rot of chickpea (Bakr and Ahmed 1987; Bakr

1988) and groundnut (Backman and Hammond, 1976). Also, a 74% reduction of foot rot occurred in lentil when seeds were treated with Baytan 10 DS(R) (3% Imazalil + 7.5% Triodimanol), and when treated with Vitavax-200(R) (37.5% Carboxin + 37.5% Thiram) the reduction was 40% (BARI, 1988). Overall, however, limited information is available on the control of seed-borne diseases of legumes grown in rice fallows.

5.6.3 Cultural practices

In traditional agriculture, fallow and crop rotation are widely used cultural practices to reduce disease intensity. In an integrated disease management program rotation with a non-host crop should be practiced to reduce the soilborne inoculum. For example, one year crop rotation with cereals such as maize (*Zea mays*) and sorghum (*Sorghum bicolor*) is effective in preventing severe infection of *S. rolfsii* in groundnut. Two to four year rotations are recommended if severe infection has developed (Backman 1984). Rotation is very effective in the case of wilt pathogens having a restricted host range. Though, the pathogens such as *S. rolfsii*, *R. bataticola* and *R. solani* have a broad host range, yet crop rotation with a non-host (specially cereals) may be possible. When it is difficult to eliminate the inoculum from the soil, it is advised to avoid sowing in heavily infested fields. The fusaria causing wilt survive in the soil for longer periods. Therefore, crop rotation is only partially effective in reducing wilt incidence in chickpea. In India, early sowing of chickpea or cultivation of early-maturing cultivars can avoid high temperatures towards crop maturity (30^0 C and above), thereby reducing mortality due to dry root rot. Soil moisture is especially important for infection by *Pythium* and *Phytophthora* spp. Therefore, waterlogging in fields should be avoided to reduce plant mortality.

Appropriate tillage and residue management can markedly influence the severity of root rot in pea (Kraft et al. 1981). *Fusarium* root rot and other cortical diseases of peas are favored by environmental conditions that are adverse to root growth and plant vigor. Consequently, good tillage practices reduce the problem. *S. rolfsii* has a broad host range and survives on host debris in the field. Therefore, controlling *S. rolfsii* particularly in groundnut emphasizes the importance of sanitation (Garren 1961) and cultural practices to reduce inoculum (Mayee and Datar 1988; Rodriguez-Kabana et al. 1991). The cultural practices include roguing, increasing plant spacing, eliminating weed hosts and removing host tissues from the soil surface. Legumes should not be sown under wet soil conditions if seed rot and pre-emergence damping off is to be reduced. Rotation of groundnut with wheat and maize is also an effective cultural practice against stem rot (Minton et al. 1991); this is a common practice in parts of northern India and China.

5.7 Insect control

A number of tactics have been developed to control insect pests of legume crops. These tactics include host plant resistance, enhanced biological control, cultural control and chemical control. Of these, the most common and effective strategy for controlling seedling pests is the need-based use of insecticides, applied either to the soil or as a seed dressing (Logan et al. 1992). Systemic insecticides used for seedling pests have fewer non-target effects and are more selective than are applications of contact foliar insecticides. In addition, these compounds are usually metabolized by the plant long before fruit or grain formation, minimizing the likelihood of pesticide residues. There has been limited effort at developing host plant resistance or cultural control methods for seedling legume pests, although integrated pest management options are practiced to limit yield losses caused by pod borers.

6. Research needs

Poor crop establishment is an important and widespread constraint to crops following rice. To better characterize the problem and assign research priorities, a first step would be to define the extent and nature of soil physical limitations to crop establishment under both upland and lowland RBCS of Asia. Such documentation, through systematic surveys and GIS mapping, would provide a sound basis for planning specific research requirements and applying established alleviation methods. There is a need to derive a classification of post-rice cropping environments based on soil type and moisture regime, so that extrapolation domains can be defined (Patanothai and Ong 1987).

Most of the soil physical limitations to establishment and growth of crops after rice have their origins in poor structure of the surface soil in combination with compacted subsoils. The problems are exacerbated by either waterlogging or a rapid rate of surface soil drying. Further research is required to study the effect of seedbed soil structure and compaction on the germination and establishment of legumes and evaluate the potential of Ca-ameliorants and crop residues for improving the surface soil structure. There is a need for research to understand reasons for response to gypsum amendment and application of mulch in some, but not all, soils.

Rice fallows have relatively hard soil compared to cultivated upland fields and hence seedling vigor plays an important role in crop establishment in rice fallows. Little directed research has been done to estimate optimum vigor of germination, and root and shoot growth, for better establishment of legumes in rice fallows. There is a need to compare vigor differences among genotypes of a given legume species and among species to evaluate their suitability for establishment in rice fallows. Understanding of the effects of soil moisture content on the mobilization of seed reserves and its effect on the seed reserve-use efficiency is lacking. The effect of moisture stress on partitioning to roots in grain legume seedlings is also worthy of further study.

Plant density and spatial arrangement can have a major effect on the final yield of most legumes. Optimum plant population varies for different plant types in the different moisture regimes. However, for a given crop, generally only one plant population (spacing) is recommended for all conditions (Patanothai and Ong 1987). There is a need to determine optimum plant population ranges for the individual food legumes under different conditions. To avoid large scale expensive field research on this seemingly simple agronomic information, use of simulation modeling will be desirable. A wealth of data is available on the effect of sowing date and soil conditions, which could be utilized to simulate rice-based cropping systems.

Efforts should be made to more specifically adapt legumes of high production potential to post-rice environments. This will require targetted breeding efforts, incorporating traits that would alleviate major constraints faced by currently grown legume cultivars or landraces. Sustainable disease management practices without reducing crop productivity, use of less susceptible cultivars, healthy seeds, limited and targetted use of chemicals and use of biological agents to manage pathogens need to be developed to reduce crop losses. Further studies are required to characterize the importance of seed-borne diseases of grain legumes and losses caused by them in the rice-based system to develop strategies for their control and management. Little is known about the effect of different cropping systems on soil micro-organisms in general, and the perpetuation and survival of soilborne pathogens of legumes in particular. More effort is also needed to enhance the effects of beneficial organisms such as rhizobia and mycorhizae, in the post-rice environment.

Various seed treatment methods offer promise in alleviating, even simultaneously, many of the constraints facing legume establishment after rice. These include seed priming, *Rhizobium* inoculation, pesticide application and pelleting with lime, rock phosphate or needed nutrients. Studies on optimum combinations for specified post-rice environments are needed.

Improvement of land preparation lies in the improvement of farm equipment. There is a need for development of implements with low draft suitable for operation with animals. To facilitate other management operations such as land levelling, drainage and sowing, different types of farm equipment are required. Therefore, research efforts are needed for the development of low-cost farm implements so that small farmers can afford to use them (So and Woodhead 1987). Minimum and/or no-tillage is becoming popular in the rice-wheat cropping systems in the Indo-Gangetic Plain and needs further study.

There are increasing urgencies to diversify cropping in rice-based systems, to sustain such cereal-dominated systems and to obtain a greater quantum and range of food materials from them. Legumes are prime candidates for crop diversification due to their ability to improve soil conditions for the cropping system as a whole, by additions of fixed N as well as a range of non-N effects. Their increased production is also needed to diversify human diets, now being threatened in some major rice-growing areas (e.g. South Asia) by cereal domination (i.e., more grain legumes are needed to provide additional protein, vitamins, and minerals, than are available in cereals). Thus, greater use needs to be made of the many rice fallows, even in densely populated parts of Asia (e.g., in Bangladesh). Therefore, research and development efforts to ensure better establishment of legumes in rice fallows need greater emphasis.

References

Angus, J.F., Hasegawa, S., Hsiano, T.G., Liboon, S.D., and **Zandstra, H.G.** 1983. The water balance of post-monsoonal dryland crops. Journal of Agricultural Science 101:699-710.

Angus, J.F., Cunningham, R.B., Moncur, M.W., and **Mackenzie, D.H.** 1981. Phasic development in field crops 1. Thermal response in the seedling phase. Field Crops Research 3:365-378.

Ayers, A.D., and **Eberhard, D.L.** 1960. Response of edible broad bean to several levels of salinity. Agronomy Journal 52:110-111.

Backman, P.A. 1984. Stem rot. *In* Compendium of peanut diseases (Porter, D.M., Smith, D.H., and Rodriguez-Kabana, R., eds.). The American Phytopathological Society, Pilot Knob, St. Paul, Minnesota, USA. pp.15-16.

Backman, P.A., and **Hammond, J.M.** 1976. Germination losses associated with delayed application of seed treatment fungicides after peanut shelling. Plant Disease Reporter 60:1-3.

Bakr, M.A. 1988. Effect of pre-sowing chemical seed treatment in controlling collar rot disease of chickpea. Abstracts of the Bangladesh Science Conference, 13 (Section 1): 90.

Bakr, M.A., and **Ahmed, F.** 1987. Effect of presowing fungicidal seed treatment in controlling *fusarium* wilt of chickpea. Abstracts of the Bangladesh Science Conference, 12 (Section 1):77.

Balasubrahmanian, V., and **Sinha, S.K.** 1976. Effects of salt stress on growth, nodulation and nitrogen fixation in cowpea and mung beans. Physiologia Plantarum 36:197-200.

Baldev, B., 1988. Origin distribution, taxonomy and morphology. *In* pulse crops (Baldev, B., Ramanujam, S., and Jain, H.K., eds.). New Delhi, India: Oxford & IBH Publishing Co. Pvt. Ltd., pp.3-51.

BARI (Bangladesh Agricultural Research Institute), 1991. Advances in Pulse Research in Bangladesh: Proceedings of the Second National Workshop on Pulses, 6-8 Jun 1989, Joydebpur: Bangladesh and Patancheru, Andhra Pradesh 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. 254 pp.

BARI (Bangladesh Agricultural Research Institute), 1988. Plant Pathology Division, Annual Report 1987/88. Joydebpur, Gazipur, Bangladesh: BARI. 116 pp.

Bouaziz, A., and **Bruckler, L.** 1989. Modeling wheat seedling growth and emergence: I. Seedling growth affected by soil water potential. Soil Science Society of America Journal 53: 1832-1838.

Brakke, M.P., and **Gardner, F.P.** 1987. Juvenile growth in pigeonpea, soybean, and cowpea in relation to seed and seedling characteristics. Crop Science 27:311-316.

Braunack, M.V., and **Dexter, A.R.** 1989. Soil aggregates in the seedbed: a review. I. Properties of aggregates and bed of aggregates. Soil and Tillage Research 14:259-279.

Brenneman, T.B., Branch, W.D., and **Csinos, A.S.** 1990. Partial resistance of southern Runner, *Arachis hypogaea*, to stem rot caused by *Sclerotium rolfsii*. Peanut Science 17:65-67.

Campbell, W.V., and **Reed, W.** 1987. Limits imposed by biological factors: Pests *in* Food legume improvement for Asian farming systems (Wallis, E.S., and Byth, D.E., eds.). Proceedings of an international workshop held at Khon Kaen University, Thailand, 1-5 September 1986. ACIAR Proceedings No. 18, Canberra, Australia. pp. 128-137.

Carangal, V.R. 1985. Soybean in rice-based farming systems. The IRRI experience *in* Soybean in Tropical and Subtropical Cropping Systems (Shanmugasundaram, S., and Sulzberger, E.W., eds.). The Asian Vegetable Research and Development Centre, Shanhua, Taiwan, China. pp. 25-36.

Carangal, V.R., Rao, M.V., and **Siwi, B.H.** 1987. Limits imposed by management in irrigated farming systems *in* Food legume improvement for Asian farming systems (Wallis, E.S., and Byth, D.E., eds.). Proceedings of an international workshop held at Khon Kaen University, Thailand, 1-5 September 1986. ACIAR Proceedings No. 18, Canberra, Australia, pp. 64-71.

Cass, A., Gusli, S., and **MacLeod, D.A.** 1994. Sustainability of soil structure quality in rice paddy-soyabean cropping systems in South Sulawesi, Indonesia. Soil and Tillage Research 31:339-352.

Chong, K., Wynne, J.C., Elkan, G.H., and **Schneeweis, T.G.** 1987. Effects of soil acidity and aluminium content on *Rhizobium* inoculation, growth and nitrogen fixation of peanuts and other grain legumes. Tropical Agriculture 64:97-104.

Choudhary, M.A., and **Pandey, R.K.** 1986. Extending limits to legume crop establishment in rainfed lowland rice *in* Food legume improvement for Asian farming systems (Wallis, E.S., and Byth, D.E., eds.). Proceedings of an international workshop held at Khon Kaen University, Thailand, 1-5 September 1986. ACIAR Proceedings No. 18, Canberra, Australia. pp. 235-239.

CIMMYT. 2000. CIMMYT in 1999-2000. Science and Sustenance. Mexico, D.F.: CIMMYT. 72 pp.

Collis-George, N., and **Hector, J.B.** 1966. Germination of seeds as influenced by matric potential and by area of contact between seed and soil water. Australian Journal of Soil Research 4:145-164.

Cook, S.M.F. 1989. Influence of soil physical properties on mung bean emergence in rice soils. M.Sc. Thesis, University of Minnesota, St. Paul, USA.

Cook, S.M.F., Gupta, S.C., Woodhead, T., and **Larson, W.E.** 1995. Soil physical constraints to establishment of mung beans (*Vigna radiata* L. Wilczek) in paddy rice (*Oryza sativa* L.) soils. Soil and Tillage Research 33:47-64.

Covell, S., Ellis, R.H., Roberts, E.H., and **Summerfied, R.J.** 1986. The influence of temperature on seed germination rate in grain legumes 1. A comparison of chickpea, lentil, soyabean, and cowpea at constant temperatures. Journal of Experimental Botany 37:705-715.

Dasberg S., and **Mendel, K.** 1971. The effect of soil water and aeration on seed germination. Journal of Experimental Botany 22:992-998.

De Datta, S.K. 1981. Principles and practices of rice production. New York, USA: John Wiley and Sons. p. 618.

Dexter A.R. 1988. Advances in Characterization of soil structure. Soil and Tillage Research 11:199-238.

Elkins, CB., Halland, R.L., and **Loveland, C.S.** 1977. Grass roots as a tool for penetrating soil hardpan and increasing crop yields. Proceedings of 34th Southern Pastures and Forage Crop

Improvement Conference, Auburn University, Auburn, Alabama, USA. pp. 21-26

Ellis, R.H., and **Roberts, E.H.** 1980. Influence of temperature and moisture on seed viability period in barley (*Hordeum distichum* L.) Annals of Botany 45:31-37.

Ellis, R.H., Simon, G., and **Covill, S.** 1987. The influence of temperature on seed germination rate in grain legumes III. A comparison of five faba bean genotypes at constant temperatures using a new screening method. Journal of Experimental Botany 38:1033-43.

Faris, D.G., Gowda, C.L.L., and **Han, Thein** (eds.), 1992. Managing AGLN crops in rice-based cropping systems: Summary proceedings of the Myanmar-AGLN/ICRISAT Workshop and Monitoring Tour. 17-25 Jan 1992, Yangon and Yezin, Myanmar. Patancheru, Andhra Pradesh 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. 76 pp.

Fyfield, T.P. 1987. Effect of temperature, water and cultivation on the establishment of a mung bean crop following paddy rice. Ph.D. Thesis. Department of Soil Science, University of Reading, UK. 145 pp.

Garren, K.H. 1961. Control of *Sclerotium rolfsii* through cultural practices. Phytopathology 51:120-124.

Green, D.E., Pinnell, E.L., Cavanagh, L.E., and **Williams, L.F.** 1965. Effect of planting date and maturity date on soybean seed quality. Agronomy Journal 57:165-168.

Greenland, D.J. 1985, Physical aspects of soil management for rice-based cropping systems *In* Soil Physics and Rice. Proceedings of workshop on physical aspects of soil management in rice-based cropping systems, 10-14 Dec., 1984. International Rice Research Institute, Los Baños, Laguna, Philippines. pp. 1-16.

Grimes, D.W., Miller, R.J., and **Wiley, P.L.** 1975. Cotton and corn root development in two field soils of different strength characteristics. Agronomy Journal 67:519-523.

Hadas, A., and **Russo, D.** 1974. Water uptake by seeds as affected by water stress, capillary conductivity and seed-soil water contact. Indian Experimental study. Agronomy Journal 66:643-647.

Hadas, A., Wolf, D., and **Meirson, I.** 1978. Tillage implements-soil structure relationships and their effects on crop stands. Soil Science Society of America Journal 42: 632-637.

Hadas, A. 1985. Water transfer to germinating seeds as affected by soil hydraulic properties and seed-water contact impedance. *In* Heat and Mass Transfer in the Biosphere. I. Transfer processes in the plant environment (De Vries D.A., and Afgan, N.H., eds.). New York, USA: John Wiley and Sons. pp. 501-511.

Hafeez, F.Y., Aslam, Z., and **Malik, K.A.** 1988. Effect of salinity and inoculation on growth, nitrogen fixation and nutrient uptake of *Vigna radiata* L. Wilczek. Plant and Soil 106:3-8.

Hanks, R.H., and **Thorp, F.C.** 1956. Seedling emergence of wheat as related to soil moisture content, bulk density, oxygen diffusion rate, and crust strength. Soil Science Society of America Proceedings 20:307-310.

Harrington, J.F. 1963. Practical advice and instructions on seed storage. Proceedings of the International Seed Testing Association 28:989-994.

Harris, D., Joshi, A., Khan, P.A., Gothkar, P. and **Sodhi, P.S.** 1999. On-farm seed priming in semi-arid agriculture: development and evaluation of maize, rice and chickpea in India using participatory methods. Experimental Agriculture 35:15-29.

Heslehurst, M.R., Imrie, B.C., and **Butler, J.E.** 1987. Limits to productivity and adaptation due to preharvest and postharvest factors. *In* Food legume improvement for Asian farming system (Wallis, E.S., and Byth, D.E., eds.). Proceedings of an international workshop held at Khon Kaen University, Thailand, 1-5 September 1986. ACIAR Proceedings No. 18, Canberra, Australia. pp. 169-182.

Howell, R.W., Collins, F.J., and **Sedgwifk, J.E.** 1959. Respiration of soybean seeds as related to weathering losses during ripening. Agronomy Journal 51:677-679.

Hundal, S.S., and **De Datta, S.K.** 1982. Effect of dry-season soil management of water conservation for the succeeding rice crop in a tropical soil. Soil Science Society of America Journal 46:1081-1086.

Ide, G., Hofman, G., Ossemerct, C., and **van Ruymbeke, M.** 1984. Root-growth response of winter barley to subsoiling. Soil and Tillage Research 4:419-431.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. ICRISAT Annual Report 1986. ICRISAT, Patancheru, Andhra Pradesh, India.

IRRI (International Rice Research Institute). 1985. IRRI Annual Report 1984. IRRI, Los Baños, Philippines.

IRRI (International Rice Research Institute). 1987. IRRI Annual Report 1986. IRRI, Los Baños, Philippines.

Jones, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. Soil Science Society of America Journal 47:1208-1211.

Kilen, T.C., and **Hartwig, E.E.** 1978. An inheritance study of impermeable seed in soybeans. Field Crops Research 1:65-70.

Kirchhof, G., and **So, H.B.** 1995. Legumes after rainfed lowland rice. ACIAR Food Legumes Newsletter 22:2-5.

Klodpeng, T., and **Morris, R.A.** 1984. Drainage of a Tropaqualf before and after water extraction by a crop. Soil Science Society of America Journal 48:632-635.

Kraft, J.M., Burke, D.W., and **Haglund, W.A.** 1981. *Fusarium* diseases of beans, peas and lentils. *In Fusarium:* Diseases, Biology and Taxonomy (Nelson, P.E., Toussoun, T.A., and Cook, R.J., eds.), Pennsylvania State University Press, Pennsylvania, USA. pp. 142-156.

LaHaye, P.A., and **Epstein, E.** 1969. Salt tolerance by plants: enhancement with calcium. Science 166:395-396.

Lal, S.S., Yadav, C.P., and **Dias, C.A.R.** 1981. Major pest problems of pigeonpea in Uttar Pradesh, India. International Pigeonpea Newsletter 1:30-31.

Larson, W.E. 1964. Soil parameters for evaluating tillage needs and operations. Soil Science Society of America Proceedings 28:118-122.

Lateef, S.S., and **Reed, W.** 1990. Insect pests on pigeonpea. *In* Insect Pests of Tropical Food Legumes (Singh, S.R., ed.). New York, USA: John Wiley and Sons. pp. 193-242.

Lauchli, A. 1984. Salt exclusion : an adaptation of legume crops and pastures under saline

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conditions. *In* salinity tolerance in plants. Strategies for crop improvement (Staples, R.C., and Toenniesen, G.H., eds.). New York, USA: John Wiley and Sons. pp. 171-187.

Lauchli, A., and **Epstein, E.** 1979. Transport of potassium and rubidium in plants roots. The significance of calcium. Plant Physiology 45:639-641.

Lauchli, A., and **Wieneke, J.** 1979. Studies on growth and distribution of Na^+, K^+ and Cl^- in Soybean varieties differing in salt tolerance. Z. Pflanzenernahr Bodenkd 142:3-13.

Lauchli, A. 1981. Mineral nutrition of plants exposed to salinity stress. *In* The problem of salinity in Agriculture: A conference on Biosalinity (Rains, D.W., ed.). University of California, Davis, USA. pp. 63-69.

Lauter, D.J., Munns, D.N., and **Clarkin, K.L.** 1981. Salt response of chickpea as influenced by N supply. Agronomy Journal 73:961-966.

Lawn, R.J., and **Williams, J.H.** 1986. Limits imposed by climatological factors. *In* food legume improvement for Asian farming systems (Wallis, E.S., and Byth, D.E., eds.). Proceedings of an international workshop held at Khon Kaen University, Thailand, 1-5 September 1986. ACIAR Proceedings No. 18, Canberra, Australia. pp. 83-98.

Leong, S.K., and **Ong C.K.** 1983. The influence of temperature and soil water deficit on the development and morphology of groundnut (*Arachis hypogaea* L.). Journal of Experimental Botany 34:1551-1561.

Letey, J. 1985. Relationship between soil physical properties and crop production. Advances in Soil Science 1:277-294.

Liao, B.S., Wang, Y.Y., Xia, X.M., Tang, G.Y., Tan, Y.J., and **Sun, D.R.** 1990. Genetic and breeding aspects of resistance to bacterial wilt in groundnut. *In b*acterial wilt of groundnut (Middleton, K.J., and Hayward, A.C., eds.). Proceedings of an ACIAR/ICRISAT collaborative research planning meeting held at Genting Highlands, Malaysia, 18-19 March 1980. ACIAR Proceedings No. 31, Canberra, Australia. pp. 39-43.

Lindstrom, M.J., Papendick, R.I., and **Koehler, F.E.** 1976. A model to predict winter wheat emergence as affected by soil temperature, water potential, and depth of planting. Agronomy Journal 68:137-141.

Lips, S.H., Leidi, E.O., Silberbush, M., Soares, I.M., and **Lewis, O.E.M.** 1990. Physiological aspects of ammonium and nitrate fertilization. Journal of Plant Nutrition 13(10):1271-1289.

Litsinger, J.A., Quirino, C.B., Lumaban, M.D., and **Bandong, J.P.** 1978. The grain legume pest complex of rice-based cropping systems at three locations in the Philippines. *In* Pests of Grain Legumes: Ecology and Control (Singh, S.R., van Emden, H.F., and Ajibola Taylor, T., eds.). Academic Press, New York, USA. pp. 309-320.

Logan, J.W.M., Rajagopal, D., Wightman, J.A., and Pearce, M.J. 1992. Control of termites and other soil pests of groundnuts with special reference to controlled release formulations of non-persistent insecticides in India and Sudan. Bulletin of Entomological Research 82:57-66.

Maas, E.V., and **Hoffman, G.J.** 1977. Crop salt tolerance - current assessment. Journal of the

Irrigation and Drainage Division. American Society of Civil Engineers 103:115-134.

Maghari, S.G., and **Woodhead, T.** 1984. Tillage in a rainfed lowland cropping sequence. Paper presented to a Saturday seminar at IRRI, Los Baños, Philippines.

Mayee, C.D., and **Datar, V.V.** 1988. Diseases of groundnut in the Tropics. Review of Tropical Plant Pathology 5:85-118.

McGarry, D. 1987. The effect of soil water content during land preparation on aspects of soil physical condition and cotton growth. Soil and Tillage Research 9:287-302.

McGarry, D. 1989. The effect of wet cultivation on the structure and fabric of a Vertisol. Journal of Soil Science 40:199-207.

McGarry, D., and **Daniells, I.G.** 1987. Shrinkage curve indices to quantify cultivation effects on soil structure of a Vertisol. Soil Science Society of America Journal 51:1575-1580.

Mehan, V.K. 1988. The mycotoxin problems. *In* Groundnut (Reddy, P.S., ed.). Indian Council of Agricultural Research (ICAR), New Delhi, India. pp. 526-541.

Middleton, K.J., Pandey, S., Sharma, S.B., and **Smith, D.H.** 1994. Diseases *in* The Groundnut Crop: A scientific basis for improvement (Smartt, J., ed.). Chapman & Hall Ltd. Scientific, Technical & Medical Publishers. pp. 336-394.

Minton, N.A., Csinos, A.E. Lynch, R.E., and **Brenneman, T.B.** 1991. Effects of two cropping and two tillage systems and pesticides on peanut pest management. Peanut Science 18: 41-46.

Mohamed, A., Barnett, F.L., Vanderlip, R.L., and **Khaleeq, B.** 1989. Emergence and stand establishment of pearl millet as affected by mesocotyl elongation and other seedling traits. Field Crops Research 20:41-49.

Monteith J.L. 1991. Weather and water in the Sudano-Sahelian zone. *In* Soil water balance in the Sudano-Sahelian Zone (Sivakumar, M.V.K., Wallace, J.S., Renard, C., and Giroux, C., eds.). Proceedings of International Workshop, Niamey, Niger. Feb. 1991. IAHS publication No. 199, IAHS Press, Institute of Hydrology, Wallingford, UK. pp. 11-29.

Mugnisjah, W.Q., and **Nakamura, S.** 1984. Vigour of Soybean seed produced from different nitrogen and phosphorus fertilizer application. Seed Science and Technology 12:475-482.

Narayanan, A., Saxena, N.P., and **Sheldrake, A.R.** 1981. Varietal differences in seed size and seedling growth of pigeonpea and chickpea. Indian Journal of Agricultural Science 51:389-393.

Nasr, H.M., and **Selles, F.** 1995. Seedling emergence as influenced by aggregate size, bulk density, and penetration resistance of the seedbed. Soil and Tillage Research 34:61-76.

Nene, Y.L., Haware, M.P., Reddy, M.V., Phillips, J.C., Castro, E.L., Kotasthane, S.R., Gupta, Om, Singh, G., Shukla, P., and **Sah, R.P.** 1989a. Identification of broad-based and stable resistance to wilt and root-rots in chickpea. Indian Phytopathology 42:499-505.

Nene, Y.L., Kannaiyan, J., Reddy, M.V., Zote, K.K., Mahmood, M., Hiremath, R.V., Shukla, P., Kotasthane, S.R., Sengupta, K., Jha, D.K., Haque, M.F., Grewal, J.S., and **Pal, M.,** 1989b. Multilocation testing of pigeonpea for broad-based resistance to *fusarium wilt* in India. Indian Phytopathology 42:449-453.

Nivedita, M. 1992. Effect of moisture status and bulk density on germination and emergence of pearl millet, sorghum and groundnut on an Alfisol. M.Sc. thesis. Andhra Pradesh Agricultural

University, Rajendranagar, Hyderabad, India. 144 pp.

Noble, C.L., and **Rogers, M.J.E.** 1993. Response of temperate forage legumes to waterlogging and salinity. *In* Hand book of plant and crop stress (Pessarakli, M., ed.). New York, USA: Mazal Pekker, Inc. pp. 473-496.

Odongo, J.C.W., Sharma, M.M., and **Ong, C.K.** 1991. Influence of temperature on seed germination of pigeonpea genotypes. *In* proceedings of International Seed Symposium (Sen, D.N., and Mohammed, S., eds.). Jodhpur, India, 27-29 Jan. 1990. pp. 293-298.

Omanga, P.A., Summerfield, R.J., and **Qi, A.** 1995. Flowering of pigeonpea (*Cajanus cajan*) in Kenya: Responses of early-maturing genotypes to location and date of sowing. Field Crops Research 41:25-34.

Pandey, R.K. 1984. Grain legumes in rice-based cropping systems. *In* Grain Legumes in Asia: Summary of Proceedings of the Consultative Group Meeting for Asian Regional Research on Grain Legumes, held during 11-15 December 1983 at International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India. pp. 85-88.

Patanothai, A. 1985. Transfer of farmers' technology, another approach in farming systems research: a case of groundnut after rice in northeast Thailand. Proceedings of the international conference on multiple cropping systems. Nanjing, China, 9-12 October 1985. Beijing, China: Chinese Academy of Agricultural Science.

Patanothai, A., and **Ong, C.K.** 1987. Limits Imposed by Management in Rainfed Farming Systems. *In* Food legume improvement for Asian farming systems (Wallis, E.S., and Byth, D.E., eds.). Proceedings of an international workshop held at Khon Kaen University, Thailand, 1-5 September 1986. ACIAR Proceedings No.18, Canberra, Australia. pp. 72-82.

Paul, S.R., and **Ramaswamy, K.R.** 1979. Relationship between seed size and seed quality attributes in cowpea (*Vigna sinensis* L. Savi). Seed Research 7:63-70.

Prasadinin, P.P., Rao, C.N., Rao, S.R., and **Rao, M.S.** 1993. Effect of tillage on physical properties of soil and yield of groundnut in a rice-based cropping system. International Rice Research Newsletter 18(1):44.

Prihar, S.S., Ghildyal, B.P., Painuli, D.K., and **Sur, H.S.** 1985. Physical properties of mineral soils affecting rice-based cropping systems. *In* Soil Physics and Rice. Proceedings of workshop on physical aspects of soil management in rice-based cropping system. International Rice Research Institute, Los Baños, Philippines. pp. 57-70.

Qadar, A. 1994. Physiology of salt tolerance. *In* Salinity management for sustainable agriculture (Rao, D.L.N., Singh, N.T., Gupta, R.K., and Tyagi, N.K., eds.). Central Soil Salinity Research Institute, Karnal, India. pp. 65-88.

Ramakrishna, A., Anders, M.M., and **Flower, D.J.** 1992. Rice-based Cropping Systems-ICRISAT's Experience. *In* Managing AGLN crops in rice-based cropping system: Summary Proceedings of the Myanmar-AGLN/ICRISAT Workshop and Monitoring Tour, 17-25 Jan., 1992. Myanmar: Yangon and Yezin, Patancheru, Andhra Pradesh, India, International Crops Research Institute for the Semi-Arid Tropics. pp. 55-58.

Rangaiah, P.V., and **Sehgal, V.K.** 1984. Insects on T 21 pigeonpea and losses caused by them at Pantnagar, northern India. International Pigeonpea Newsletter 3:40-43.

Reed, W., Cardona, C., Sithanantham, S., and **Lateef, S.S.** 1987. Chickpea insect pests and their control. *In* The Chickpea (Saxena, M.C., and Singh, K.B., eds.). CAB International, UK: Wallingford, pp. 283-318.

Rego, T.J., Nageswara Rao, V., and **Kumar Rao, J.V.D.K.** 1998. Long-term consequences of legumes in rice-wheat system in the Indo-Gangetic Plains (Kumar Rao, J.V.D.K., Johansen, C., and Rego, T.J., eds.). *In* Proceedings of the Workshop on Residual effects of Legumes in Rice-Wheat Cropping Systems of the Indo-Gangetic Plains. ICRISAT Patancheru, Andhra Pradesh, India and New Delhi, India: Oxford and IBH Publishing House.

Richard, G., and **Guerif, J.** 1988. Influence of aeration conditions in the seedbed on sugar beet seed germination: Experimental study and model. Proceeding of 11th ISTRO International Conference. UK: Edinburgh. Vol. 1:103-108.

Rodriguez-Kabana, R., Robertson, D.G., Wells, L., Weaver, C.F., and **King, P.S.** 1991. Cotton as a rotation crop for the management of *Meloidogyne arenaria* and *Sclerotium rolfsii* in peanut. Journal of Nematology 23:652-657.

Rupela, O.P., Toomsan, B., Mittal, S., Dart, P.J., and **Thompson, J.A.** 1987. Chickpea *Rhizobium* populations: Survey of influence of season, soil depth and cropping pattern. Soil Biology and Biochemistry 19:247-252.

Rupela, O.P. 1997. Field evaluation of some recently developed selections for high nodulation and value of nodulation variants of chickpea. Pages 305-317 in (Rupela, O.P., Johansen, C., and Herridge, D.F., eds.). Extending nitrogen fixation research to farmers' fields: proceeding of an International Workshop on Managing Legume Nitrogen Fixation in Cropping Systems of Asia, 20-24 Aug 1996, ICRISAT Asia Center, India, Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Russell, E.W. 1973. Soil conditions and plant growth. 10th edition. London: Longman, Green and Co. 849 pp.

Sattar, M.A., Khanam, D., Ahmad, S., Haider, M.R., Podder, A.K., and **Bhuiyan, M.A.H.** 1997. On-farm experiments on rhizobial inoculants in Bangladesh: results, problems,and possible solutions. Pages 201-216 in (Rupela, O.P., Johansen, C., and Herridge, D.F., eds.) Extending nitrogen fixation research to farmers' fields: proceedings of an International Workshop on Managing Legume Nitrogen Fixation in the Cropping Systems of Asia, 20-24 Aug 1996, ICRISAT, India, Patancheru 502 324, Andhra Pradesh, India. International Crops Research Institute for the Semi-Arid Tropics.

Satyanarayana, A., Seenaiah, P., Sudhakara Babu, K., and **Prasad Rao, M.P.** 1994. Extending pulses production in rice fallows. Paper presented at the International Symposium on Pulses Research, New Delhi: India. 23 pp.

Saxena, K.B., Chauhan, Y.S., Laxman Singh, Kumar, R.V., and **Johansen, C.** 1996. Research and development of hybrid pigeonpea. Research Bulletin no. 19. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Padesh, India. 20 pp.

Saxena, N.P., Narayanan, A., and **Sheldrake, A.R.** 1981. Effect of seed grading on the yields of chickpea and pigeonpea. Indian Journal of Agricultural Science 51:699-702.

Saxena, N.P. 1987. Screening for adaptation to drought. Case study with chickpea and pigeonpea. *In* Adaptation of chickpea and pigeonpea to abiotic stresses. Proceedings of the Consultants' Workshop, 19-21 December 1984, ICRISAT, Patancheru, India, pp. 63-76.

Schneider, E.C., and **Gupta, S.C.** 1985. Corn emergence as influenced by soil temperature, matric potential, and aggregate size distribution. Soil Science Society of America Journal 49:415-422.

Shanower, T.G., Wightman, J.A., and **Gutierrez, A.P.** 1993. Biology and control of the groundnut leafminer, *Aproaerema modicella* (Deventer) (Lepidoptera: Gelechiidae). Crop Protection 12:3-10.

Sharma, P.K., and **de Datta, S.K.** 1985. Effects of puddling on soil physical properties and processes. *In* Soil Physics and Rice. International Rice Research Institute, Los Baños, Laguna, Philippines, pp. 217-234.

Singh, K.N. 1994. Crops and agronomic management. *In* Salinity management for sustainable agriculture (Rao, D.L.N., Singh, N.T., Gupta, R.K., and Tyagi, N.K., eds.). Central Soil Salinity Research Institute, Karnal, India. pp. 124-144.

Singh, R.N., and **Singh, K.M.** 1978. Succession of insect pests in early varieties of red gram, *Cajanus cajan* (L.) Millsp. Indian Journal of Entomology 40:1-6.

Sivakumar, M.V.K., and **Virmani, S.M.** 1984. Crop productivity in relation to interception of photosynthetically active radiation. Agricultural and Forest Meteorology 31:131-141.

Smith, T.J., and **Camper, H.M., Jr.** 1975. Effects of seed size on soybean performance. Agronomy Journal 67:681-684.

So, H.B., and **Woodhead, T.** 1987. Alleviation of Soil Physical Limits to Productivity of Legumes in Asia. *In* Food legume improvement for Asian farming systems (Wallis, E.S., and Byth D.E., eds.). Proceedings of an international workshop held at Khon Kaen University, Thailand, 1-5 September 1986. ACIAR Proceedings No.18, Canberra, Australia, pp. 112-120.

Squire, G.R. 1990. The physiology of tropical crop production. Wallingford: UK, CAB International. 250 pp.

Stout, B.A., Buchele, W.F., and **Snyder, F.W.** 1961. Effect of soil compaction on seedling emergence under simulated field conditions. Agricultural Engineering 42:68-71.

Syarifuddin, A., and **Zandstra, H.G.** 1978. Growing rainfed corn and soybean after puddled flooded rice II. Soil Chemical Conditions and management. IRRI Saturday Seminar. 18 November 1978. International Rice Research Institute, Los Baños, Laguna, Philippines, 15 pp.

Tackett, J.L., and **Pearson, R.W.** 1964. Oxygen requirements of cotton seedling roots for penetration of compacted soil cores. Soil Science Society of America Proceedings 28:600-605.

Taylor, H.M., and **Gardner, H.R.** 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. Soil Science 96:153-156.

Taylor, H.M., and **Ratliff, L.F.** 1969. Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Science 108:113-119.

Taylor, H.M., Roberson, G.M., and **Parker, J.J.** 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Science 102:18-22.

Thompson, J.P. 1987. Decline of vesicular-arbuscular mycorrhizae in long fallow disorder of field crops and its expression in phosphorous deficiency of sunflower. Australian Journal of Agricultural Research 38:847-867.

Troedson, R.J., Lawn, R.J., and **Byth, D.E.** 1985. Water management for peak soybean production on clay soils. *In* Root zone limitations to crop production on clay soils. (Muirhead, W.A., and

Humphreys, E., eds.). Proceedings of Symposium of the Australian Soil Science. Griffith: Australia.

Vepraskas, M.J. 1988. Bulk density values diagnostic of restricted root growth in coarse-textured soils. Soil Science Society of America Journal 52:1117-1121.

Vepraskas, M.J., and **Wagger, M.G.** 1989. Cone index values diagnostic of where subsoiling can increase corn root growth. Soil Science Society of America Journal, 53:1499-1505.

Vepraskas, M.J. 1994. Plant response mechanisms to soil compaction. *In* Plant environment interactions (Wilkinson, R.E., ed.). New York, USA: Marcel Dekker Inc. pp. 263-287.

Wanjura, D.F., Buxton, D.R., Stapleton, H.N. 1970. A temperature model for predicting initial cotton emergence. Agronomy Journal 62: 741-743.

Whalley, D.B., Mckell, C.M., and **Green, L.R.** 1966. Seedling vigor and early nonphotosynthetic stage of seedling growth in grasses. Crop Science 6:147-150.

Whiteley, G.M., Utomo, W.H., and **Dexter, A.R.** 1981. A comparison of penetrometer pressures and the pressures exerted by roots. Plant and Soil 61:351-364.

Weigel, R.C., Schillinger, J.A., McCaw, B.A., Gauch, H.G., and **Hsiao, E.** 1973. Nutrient-nitrate levels and accumulation of chloride in leaves of snap beans and roots of soybeans. Crop Science 13:411-412.

Wightman, J.A., and **Ranga Rao, G.V.** 1994. Groundnut pests. *In* The Groundnut Crop (Smartt, J., ed.). UK, London: Chapman and Hall. pp. 395-479.

Wightman, J.A., Dick, K.M., Ranga Rao, G.V., Shanower, T.G., and **Gold, C.G.** 1990. Pests of groundnut in the semi-arid tropics. *In* Insect Pests of Tropical Food Legumes (Singh, S.R., ed.). New York, USA: John Wiley and Sons. pp. 243-322.

Wilson, J.R. 1970. Response to salinity in Glycine. VI. Some effects of a range of short-term salt stresses on growth, nodulation and nitrogen fixation of *Glycine wightii* (formerly javanica). Australian Journal of Agricultural Research 21:571-582.

Wilson, J.R., and **Norris, D.O.** 1970. Some effects of salinity on G*lycine javanica* and its *Rhizobium* symbiosis. Proceeding of 11th International Grassland Congress. pp. 455-459.

Woodhead, T. 1994. Cultivation of puddled soil for dry-season legumes (Personal communication).

Zandstra, H.G. 1982. Effect of soil moisture and texture on the growth of upland crops after wetland rice. *In* Cropping Systems Research in Asia. International Rice Research Institute, Los Baños, Laguna, Philippines, pp. 42-54.

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