Management of legume nitrogen-fixation for rainfed cereal production (LWR2/1992/010); Sustainable grain legume–cereal production systems through management of nitrogen-fixation (LWR2/1997/062)

Graeme Schwenke and David Herridge

Collaborating organisations	NSW Agriculture (NSWDA), CSIRO Plant Industry, Agricultural Production Systems Research Unit (APSRU)/CSIRO Tropical Agriculture, Australia; Pakistan Agricultural Research Council (PARC), North West Frontier Province Agricultural University (NWFPAU), Peshawar Agricultural Research Institute (PARI), University for Arid Agriculture (UAA), National Agricultural Research Centre (NARI), Pakistan; Nepal Agricultural Research Council (NARC); Vietnam National University (VNU)
Project leaders	Dr David Herridge (NSWDA); Dr Muhammad Aslam (NARC); Dr Nguyen Xuan Hong (VNU)
Related projects	LWR2/1983/005, LWR2/1983/006, LWR2/1987/003, LWR2/1988/000, LWR2/1988/029, LWR2/1991/002, LWR2/1992/016, LWR2/1994/048, CS1/1996/049, LWR2/1995/710, LWR2/1995/712, LWR2/1998/027
Principal researchers	David Herridge, Graeme Schwenke, Warwick Felton, Harry Marcellos, Jill Turpin (NSW Agriculture); Mark Peoples, Graham Turner (CSIRO); Michael Robertson (APSRU/CSIRO); Zahir Shah (NWFPAU); Sabir Shah, Dil Fayaz Khan (PARI); Safdar Ali (UAA); Muhammad Aslam (NARC); Surya Maskey, Shanti Bhattarai (NARI); Nguyen Xuan Hong (VNU)

Duration of project	1 January 1994 to 31 December 1996, extension 1 January 1997 to 31 December1997 1 January 1998 to 31 December 2000, extension 1 July 2000 to 31 June 2001
Total ACIAR funding	$1,260,144; $760,471
Project objectives	These projects aimed to improve, through increased use of legumes, the productivity, profitability and sustainability of cereals-dominated cropping systems in the rainfed areas of the Punjab and NWFP of Pakistan, the Hill and Terai agro-ecological zones of Nepal, the upland systems of northern Vietnam and the northern grains belt of Australia. This was to be achieved by research to enhance the benefits of legumes and legume nitrogen-fixation in cereal-production systems and putting new knowledge to work through improved management and decision-support packages.
Location of project activities	Pakistan, Nepal, Vietnam and Australia

Overview

In the early 1990s, dryland cropping in northern Pakistan, Nepal and north-eastern Australia was characterised by a dominance of winter cereals, low use of legumes and little or no nitrogen fertiliser. Consequently, cereals were often nitrogen deficient, low yielding and their efficiency of water use was poor. These two ACIAR projects aimed to improve, through increased use and better management of crop legumes, the productivity, profitability and sustainability of cereals-dominated cropping systems in barani (dryland) areas of the Punjab and North West Frontier Province (NWFP) of Pakistan, the mid-Hill and Terai agro-ecological zones of Nepal, and the northern grains belt of Australia.

Researchers combined actual legume nitrogen (N_2)-fixation measurements from field surveys and field experiments with knowledge of factors influencing N_2-fixation to devise and test improved cropping systems that would benefit farmers, soil fertility, and the environment. While these projects were primarily about new scientific knowledge and understanding, the partner researchers and their institutions benefited greatly from the introduction of new research technologies, facilities and practical approaches used in measuring and understanding legume N2-fixation in cropping systems.

Project achievements

These two projects generated new knowledge of crop legume N2-fixation in both commercial and experimental situations over a large range of country-site-years. These results were then put to use in devising, testing, costing and modelling alternate cropping systems that have both economic and environmental benefits for farmers.

Measuring crop legume N_2-fixation

Surveys of nearly 400 commercial pulse crops indicated the great potential of well-grown pulses to fix substantial quantities of nitrogen (N). Values for Pfix (the percentage of legume N derived from N2-fixation) showed no obvious effect of species and were generally high (50–80%), with the exceptions of chickpea in Australia and soybean in Pakistan that were lower (Table 1). The data on N2-fixation and N inputs were unique and greatly enhanced our understanding of the potential of pulses (and other legumes) to increase productivity and sustainability of cropping systems. An estimate for annual legume N2-fixation in Nepal of 30,000 t N/yr was derived from the farm survey data. This amounted to A$30 million in equivalent fertiliser costs.

Photo: G. Schwenke.

Dr Sabir Hussein Shah (Director of Soil & Plant Nutrition, Tarnab Agricultural Research Institute) and Dr Zahir Shah (Professor of Soil Science, North West Frontier Province Agricultural University, Peshawar) compare healthy and nitrogen-deficient wheat plots in a farming-systems trial in the Swat River Valley, north of Peshawar, Pakistan.

Table 1. Summary of nitrogen-fixation measurements in farmers' fields in Pakistan, Syria, Lebanon, Nepal and Australia

Species	Country & region	No. of fields	Pfix (%)	N_2 fixed (kg ha^{-1})
Winter legumes				
Lentil	Pakistan – NWFP	40	78	47
	Nepal – Terai	15	77	72
	Nepal – Terai	4	84	–
	Syria, Lebanon	27	72	–
Chickpea	Pakistan – Punjab	83	75	–
	Nepal – Terai	14	79	84
	Syria, Lebanon	19	60	–
	Australia – north-west NSW	21	28	22
Fababean	Australia – north-west NSW	24	52	69
	Nepal – Hills	2	85	80
Grasspea	Nepal – Hills, Terai	4	87	80
Summer legumes				
Soybean	Pakistan – Punjab	11	16	–
	Nepal – Hills	14	66	59
Mungbean	Pakistan – NWFP	40	47	28
		12	77	–
Pigeonpea	Nepal – Terai	5	75	412
Mashbean	Nepal – Hills	20	47	28
Groundnut	Nepal – Terai	16	57	153

Legume N2-fixation was also substantial in most of the crop-rotation field experiments. Values exceeded 300 kg N/ha for irrigated pigeonpea and mungbean in the NWFP, Pakistan, and for soybean in the Hills of Nepal. More commonly, values were in the range 50–150 kg N/ha. The values for the Australian experiments were similar to those for Pakistan and Nepal.

Factors influencing N_2-fixation

Our data confirmed the strong relationship between Pfix and (a) available soil nitrate-N in the soil, and (b) the plants' demand for N to satisfy biomass production. In other words, legumes will only symbiotically fix atmospheric N2 if the plant's demand for growth cannot be met by available nitrate-N in the soil. The data from surveys of farmers' fields was identical to experimental plot data in this respect and both were used to derive empirical relationships for use in decision-support packages for farmers and advisers.

Lower Pfix values for the summer-grown mung and mashbean most likely reflected nitrate-N suppression of N2-fixation. More soil nitrate is released from organic matter mineralisation during the summer growth period when soil temperatures are high and soils are going through rapid wetting/drying cycles than in winter with its low soil temperatures and more stable moisture.

Cropping systems experiments

Given a choice, farmers would prefer to grow legumes that have a positive N balance, i.e. that add more N to the soil than is taken away in grain and other products. Data from the nine rotation experiments in northern NSW indicated N balances for chickpea ranging from -67 to +61 kg/ha, with values influenced by soil nitrate, crop growth, grain yield and N harvest index. Thus, the farmer has to manage the system, particularly for soil nitrate and biomass (and grain) yield, to ensure a positive N balance. Another key outcome of the Australian experimental program was that fababean was shown to have a greater capacity for N_2-fixation than chickpea and, when soil-nitrate supply far exceeded demand, spared soil nitrate.

In the 14 crop-rotation experiments carried out in Pakistan and Nepal, crop legumes regularly increased yields of the following cereal crops by 20–100%, relative to cereal monoculture treatments. Cereals also responded to inputs of fertiliser N, particularly in the low-N soils of Pakistan. Responses there were commonly 100–200%. Increasing productivity through incorporating legumes and fertiliser N also increased soil organic fertility. For example, after 4 years of the chickpea–wheat-rotation experiments in Pakistan, soil organic matter had increased by 28–56% through inclusion of chickpea and by 35–72% through inputs of fertiliser N in the wheat monoculture. Values for increases in soil total N were 22–56% (chickpea rotation) and 66–100% (fertiliser N on cereals).

Photo: G. Schwenke.

Dr Dil-Fayaz Khan, top, (Soil Microbiologist, Tarnab Agricultural Research Institute) passing on soil-analysis techniques he learnt during PhD study in Australia to colleagues at the North West Frontier Province Agricultural University, Peshawar.

Use of the data

Economic analyses using gross margin, dominance and marginal analysis of a number of the rotation experiments revealed large benefits of legumes, particularly chickpea and fababean in Australia, and soybean and black gram in Pakistan. The legume economic benefit reflected both its high grain price and its positive impact on yields of following cereals.

Both growth and N_2-fixation models for fababean and chickpea in the Agricultural Production systems Simulation Model (APSIM) were refined as a result of the project's field experiments at Gatton in south-eastern Queensland and through verification using other data sets. APSIM-generated simulations of part of the NWFP data sets from Swat and Dir showed good agreement with observed data for wheat (-N) and mungbean, and reasonable predictions for responses of the wheat to both legumes and fertiliser N. APSIM appears to be an excellent tool for scenario analysis (e.g. fertiliser N rates, residue management) in such systems.

Field and laboratory technique development

The xylem solute method for measuring legume N_2-fixation was calibrated for cowpea, mungbean and black gram in Australian glasshouse trials thus adding them to the list of species calibrated for this method. Sampling procedures for the method were refined and simplified with the previously recommended 7–8 samplings reduced to 1–2. The ureide method for measuring legume N_2-fixation is fast and dispenses with the need for highly specialised and expensive mass-spectrometer analyses. All the project laboratories and many others trained during the project continue to use this method in related research activities.

The difference the project has made

In northern Pakistan, projects LWR2/1992/010 and LWR2/1997/062 effectively created a mini cooperative research centre for field-based research into legumes in cropping systems. Competent but under-resourced scientists from several institutions were brought together, equipped, funded and trained in new and existing techniques of field and laboratory measurements, data interpretation and communicating results. There are also now a decade of post-graduates (nearly 30) from the two local universities involved who have graduated with applied practical research experience instead of purely theoretical studies. These graduates are now in a wide range of government departments, research institutes and university teaching positions so the network of practical understanding and experience continues to grow. The core research groups continue to attract new funding grants to further their legume N_2-fixation and soil-fertility-related research and postgraduate training. Similarly, in Nepal the project led to a considerable boost in the expertise, knowledge and experience of the project scientists and their technical staff giving them skills and understanding that have been put to use in related soil's research since the project concluded.

There is no doubt that the project research contributed greatly to an increase in the cultivation of crop legumes in the areas surrounding the ACIAR field trials in the Punjab and North West Frontier provinces of northern Pakistan, and in the Hills and Terai regions of Nepal. Farmers in these areas are now more happy with the involvement of legumes in their cropping systems and understand that legumes not only increase yields of the following crops through improved soil fertility but are profitable in themselves and may be grown on marginal lands. Although it is difficult to put figures on the perceived increase in legumes grown, reports of increasing sales of legume seed seem to be backed by official statistics for the Punjab province of Pakistan, indicating a drop in the ratio of cereals to legumes grown from 9:1 to 5:1 between 1991 and 2005.

The projects' outcomes have also impacted on the farmers in a social sense—through greater experience with growing different crops, and greater knowledge of their function within the cropping system. Understanding the benefits of growing crop legumes effectively, through attention to using rhizobial inoculation and understanding the value of retaining the crop residues, gave farmers tools to better manage their limited resources of money and land. Environmentally, greater adoption and incorporation of annual crop legumes should see less reliance on chemical fertilisers that can become groundwater and surface-water pollutants when not applied in synchrony with plant demand. Greater productivity of existing arable land may relieve some of the pressure to introduce marginal land to cultivation.

However, adoption in areas not near the experimental sites was mostly low, reflecting the largely research focus of these projects. There was no formal extension program built into the ACIAR projects, instead relying on existing institutional networks for dissemination of results—a method that has not proven very effective in capitalising on this work. Since the first project began, it has become more common for researchers in Australia to extend their research results themselves through participatory farmer research, adviser-update seminars and popular media, but in Asia this trend is just beginning. During the ACIAR project, Pakistani and Nepalese researchers saw the value of on-farm trials as extension tools firsthand. They feel the best way for increased adoption is in networks of field demonstrations and small-group training rather than printed material since many farmers are illiterate and learn most effectively by personal experiences.

In Australia the aims were similar even though the background situations were not. While most farmers do now use nitrogen fertiliser on cereals, diminishing real returns mean they welcome any means of reducing reliance on fertiliser especially with ever-increasing costs. Many farmers also have increasingly negative feelings about applying increasing amounts of chemical fertilisers to their soil and prefer more 'natural' alternatives wherever possible. With continuous cereal cropping has also come significant problems of plant diseases and difficult-to-control weeds, so annual crop legumes have additional roles to play as break crops.

Research results from these projects were incorporated into the APSIM crop-simulator model and other decision-support packages that are used by farmers and advisers looking to better understand and manage their paddock nitrogen budgets. Crop legumes are now significant components of cropping systems in some areas of north-west NSW. The main impediments to farmers in other areas growing more crop legumes have been problems with diseases and adaptation to soils with increasing salinity with depth—both topics of current research in the region.

The training workshops in measurement and management of legume N_2-fixation with scientists, students and technical staff from Pakistan, Nepal, India, Vietnam, Bangladesh, Nigeria and several other countries have engendered greater understanding of legumes and their scope for improving soil and plant systems. Previous methods used were crude, imprecise and in some cases proven to be outdated science. Realistic measures of legume N2-fixation are needed to help develop and promote more sustainable cropping systems.

Project impacts

Community impacts

Detailed community impact evaluations were outside the scope of these ACIAR projects since they were research-oriented programs. Realistically, community impacts would be low on average across the mandated farming regions. The exceptions to this are those communities in the vicinity of the field-research trials who observed firsthand that crop rotation and residue-retention treatments improve yields and profitability. These farmers are happy with growing legumes and their farm income has increased. The use of chemical N fertiliser has reduced somewhat and with this we would expect that the danger of contamination of drinking water with possible nitrate movement from fertiliser has also been reduced. Soil cover with legumes has been observed to reduce soil eroding into surface water bodies.

The overall impact may well remain minimal without further investment in a formal extension and adoption program. Several of the former ACIAR project staff did report a general impression of increased inoculant use and increased area of legume production in their regions. This is perhaps due to a gradual filtering of information from the many people updated with the projects results, including agricultural college teachers and students, extension department officers, and progressive farmers. Nevertheless, all of the former Pakistani and Nepalese project staff felt that any new investment should also include the establishment of a network of field demonstration trials throughout the dryland grain-growing areas, including areas not initially targeted by the ACIAR project, e.g. the southern districts of NWFP in Pakistan, especially Bannu and Karak, which are areas suited to chickpea and pea growing.

Capacity building

Capacity building was one of the strongest features of these two projects and its clearest legacy. This is in part because the core project team engaged at the commencement of project LWR2/1992/010 were all still actively involved at the end of project LWR2/1997/062, and continue in related research to this day. All of the core staff have been promoted within and/or outside their organisations in recognition of their scientific and professional achievements during the project period. Two are now full professors at their universities. In Pakistan particularly the core team has greatly increased its national and international reputation in the scientific community with several team members winning overseas study awards. This work has led to further research grants as well as merit-based promotions of all staff involved.

Of particular note was the development of field and laboratory research facilities and expertise at the University of Arid Agriculture (UAA), Rawalpindi, and the NWFPAU, Peshawar. With supplied vehicles, field sampling and laboratory-analysis equipment, and extensive training, each was able to conduct extensive field surveys and practical research experiments in remote farmers' fields. Quality-assurance principles and practices were introduced into the laboratory operations of the three collaborating Pakistani institutes, was supported during the project, and are now part of the training given to all new students and technical staff.

The experimental capacity developed by the ACIAR projects formed the basis of nearly 30 Masters and PhD programs both during and since the project period. Many of those students now work in positions that draw on their accumulated experience and expertise relating to soil fertility, crop rotations, legume N_2-fixation, rhizobial inoculation, and nutrient budgeting. Some have gone on to further studies overseas. The project also fostered collaboration between the universities and national research institutes as well as overseas research centres. Dr Shah from NWFPAU comments, 'It provided us with an opportunity to attend seven international scientific meetings, to develop linkages with various international organisations and also to publish our results in international publications.'

Photo: G. Schwenke.

Shabaz Ahmad, Imdad Mahmood and Dr Muhammad Aslam (researchers at the National Agricultural Research Centre) learning soil-nitrogen analysis during a training workshop on methods of measuring soil quality at North West Frontier Province Agricultural University, Peshawar, in 1997.

Scientific impacts

The projects' outputs have had far-reaching contributions to other agricultural research projects as evidenced by the continued research-funding grants awarded to the Pakistani and Nepalese researchers since the project ended. The techniques of measurement of field nitrogen-fixation and assessment of crop-nitrogen benefits to the soil and following crops are still in use today in new related research projects. The laboratories that were developed with the help of the ACIAR project team remain in constant use for teaching and research activities.

The project results were widely publicised and published, ranging from local-language brochures for farmers, to national and international scientific journal papers, scientific conference abstracts and posters, institute seminars, farmer and adviser updates, and newspaper publicity articles. The 1996 project review meeting held at the International Crop Research Institute for the Semi-arid Tropics (ICRISAT), Hyderabad, India, provided a major project outreach activity that brought the projects' results to date before an audience of scientists from across Asia and Africa. The proceedings were refereed and published jointly by ACIAR and ICRISAT in 1997 along with contributed papers from other delegates at the workshop.

In Australia, project research results have contributed significantly to the development of decision support packages for farmers and advisers. A compendium titled 'Nitrogen and legumes in northern Australian farming systems' draws heavily on information gathered as part of the ACIAR project activities in Australia. Annual crop legume information is also integral in an interactive spreadsheet program where users can view the impacts of varying crop choice and management on the nitrogen cycle in the soil–plant system. Extolling the benefits of crop legumes and improved stubble management on soil organic fertility has played an important role in the adoption of reduced and zero tillage by over 50% of cropping farmers in north-west NSW (higher in some areas).