CONTROLLING *PHALARIS MINOR* IN THE INDIAN RICE–WHEAT BELT

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Contents

Tables

Summary

- ▶▶▶▶ The ACIAR-managed project CS1/1996/013, Herbicide-resistant weeds of wheat in India and Australia: integrated management, was designed to find a long-term method of control of *Phalaris minor*, a problem weed of the rice–wheat cropping system of north-western India. By 1993, the weed had developed resistance to isoproturon, a herbicide which had delivered effective weed control for 15 years.
- ▶▶▶▶ The short-term solution, implemented before the ACIAR project commenced, involved identification and registration of a new set of herbicides. But these new herbicides were expensive. To ensure high adoption they needed to be combined with changes in wheat-growing techniques that would provide cost savings to help farmers pay for them. And to avoid the re-emergence of chemical resistance, they needed to be used sparingly as one element in a broader approach to weed management.
- ▶▶▶▶ The project team used these circumstances to field-test and encourage adoption of zero tillage, a technology that agronomists had been advocating for many years, but which had failed to capture the interest of Indian farmers.
- ▶▶▶▶ Zero tillage has the potential to deliver big cost savings. In addition, it provides prospects for yield increases by allowing early sowing of wheat and avoiding soil degradation. Project research established that zero tillage also provided effective weed control with only a moderate reliance on chemicals, making the re-emergence of herbicide resistance remote.
  - We calculate a gain to the Indian economy of around $1800 million in net present value terms over the next 30 years from the adoption of zero tillage to control *Phalaris minor* infestation in the rice–wheat areas of north-western India.
  - This leads to an extremely high ratio of benefits to project costs.
- ▶▶▶▶ Zero tillage by itself is clearly a profitable technology. It does not need a weed problem to justify its introduction. Without the ACIAR project, zero tillage would have been introduced to the region, though somewhat later than what has occurred.
- ▶▶▶▶ On the assumption that the ACIAR project has advanced the adoption profile of zero tillage by 3 years, we calculate gains that can be attributed to ACIAR's role of $238 million in net present value terms over the next 30 years. This gain has been achieved with total expenditures on the ACIAR-managed project amounting to only $1.3 million in present values.

1 Introduction

The gradual liberalisation of the Indian economy initiated in 1995 has delivered a period of sustained economic growth, principally in the manufacturing and service sectors. This is imposing adjustment pressures on agriculture, which is finding it harder to compete with faster-growing sectors for resources.

Despite this progress, agriculture still accounts for around 25% of India's gross domestic product. Some 75% of India's population of over 1 billion people live in rural areas, with many dependent directly and indirectly on agriculture for their livelihoods.

A strongly performing agriculture sector remains critical to improving the living standards of India's rural poor. With no more land available for cultivation, agricultural output growth must come through productivity improvements on existing land. Critically, these improvements must be achieved in an environmentally sustainable manner to ensure their longer-term viability.

There are growing concerns about environmental sustainability in many parts of Indian agriculture. Soil degradation is a serious problem in India, with 57% of the land undergoing degradation (Singh and Kumar 2002). The area of degraded soils continues to expand and, in many areas, watertables are falling and water quality is declining.

Projects that assist with poverty alleviation through improving agricultural productivity in ways which conserve and enhance natural resources such as soils and water seem particularly appropriate at this stage of India's economic development. The Australian Centre for International Agricultural Research (ACIAR) project CSI/1996/013 (Herbicide-resistant weeds of wheat in India and Australia: integrated management) provides a shining example of this.

2 *Phalaris minor*: a threat to agriculture in the wheat–rice belt of north-western India

Phalaris minor (littleseed canary grass) is a common weed of wheat–rice cropping systems in the north-western Indo-Gangetic Plains of India. The area of infestation is mostly contained in the states of Punjab and Haryana (Figure 1).

Figure 1. Area of *Phalaris minor* infestation (source: http://www.jayceenet.com/mapindia.htm (accessed 19 March 2002))

These two states account for around 3 million hectares of wheat–rice cropping land out of India's 10 million hectare wheat–rice cropping system and about 35% of India's wheat production.

Phalaris minor infestation has been a longstanding management problem for farmers in these states. The weed problem dates back to the green revolution of the late 1960s, which saw the introduction of dwarf wheat varieties and the improved irrigation and fertiliser practices needed to maximise their yield potential. Untreated weed infestation can result in dramatic reductions in wheat yields (the weed does not germinate in the rice part of the rotation) through farmers being forced to harvest immature crops. Complete failure of the wheat crop can occur in extreme cases.

Chemical weed control and chemical resistance

Up until the early 1990s, *Phalaris minor* could be effectively controlled by farmers spraying the crop with isoproturon, a substituted urea herbicide first recommended in 1977–78 and widely used since the early 1980s. This herbicide gave excellent weed control for 15 years. But, after this long period of continuous and heavy spraying, accentuated by poor application rates, spray techniques and timing, evidence of herbicide resistance of *Phalaris minor* to isoproturon was discovered by Malik and others in the early 1990s (Malik and Singh 1995). The development of chemical resistance led to big declines in wheat yields in some parts of Haryana and, to a lesser extent, Punjab—yield reductions of 30 to 80% were observed on individual properties. In Haryana, the percentage of farmers reporting satisfactory weed control with isoproturon fell from around 80% in 1989–90 to 20% in 1992–93.

By 1993, between 0.8 and 1 million hectares of the wheat–rice rotation in north-western India was affected by herbicide-resistant *Phalaris minor*. The effects on yield at the aggregate state level in the years immediately after this were masked by a run of favourable weather conditions and also by the rapid uptake of a new and high-yielding dwarf wheat variety, PBW-343 (which is more competitive against weeds than other varieties), over the same period (Table 1). Introduced in 1995, PBW-343 was adopted quickly and by 1999–2000 was being used on more than 4 million hectares in northern India.

In an effort to avoid massive income losses, some farmers in Haryana switched to growing sunflowers. Sunflower plantings increased from 10,000 hectares in 1993 to 60,000 hectares in 1996. Sunflower yields are only one third that of wheat. Problems with seed availability and a rapid yield decline ensured that the switch to sunflowers was not a profitable alternative for farmers affected by *Phalaris minor* incursions.

Table 1. Trends in wheat area, production and yield: Punjab and Haryana

Year	Punjab			Haryana		
	Area (million ha)	Yield (t/ha)	Production (million t)	Area (million ha)	Yield (t/ha)	Production (million t)
1990–91	3.3	3.7	12.2	1.8	3.5	6.4
1991–92	3.2	3.8	12.3	1.8	3.6	6.5
1992–93	3.3	3.8	12.4	2.0	3.6	7.1
1993–94	3.3	4.0	13.3	2.0	3.6	7.2
1994–95	3.3	4.1	13.5	2.0	3.7	7.3
1995–96	3.2	3.9	12.5	2.0	3.7	7.3
1996–97	3.2	4.2	13.7	2.0	3.9	7.8
1997–98	3.3	3.9	12.8	2.1	3.7	7.5
1998–99	3.3	4.3	14.5	2.2	3.9	8.6
1999–00	3.4	4.7	15.9	2.3	4.2	9.6
2001–01	3.4	4.6	15.5			

Source: State government statistics.

The development of herbicide resistance in weeds through continued use of the same herbicide group as the sole method of weed control is well known, particularly among Australian weed scientists. Herbicide resistance has been confirmed in 22 different weed species in Australia (Gill 2002). But flexible production and control responses adopted in Australia have curtailed the adverse economic impact of this resistance. By contrast, Malik and Singh (1995) considered the evolution of herbicide resistance of *Phalaris minor* in the wheat–rice cropping system of north-west India to be ‘the most serious case of herbicide resistance in the world, resulting in total crop failure and heavy infestation’. Their research showed that many biotypes had become resistant to isoproturon, with resistant biotypes from Haryana requiring up to eleven times the pre-susceptible dose of isoproturon to achieve 50% weed control.

New herbicides: a short-term solution

Indian weed scientists led by Dr Malik at Haryana Agricultural University (HAU) working in conjunction with chemical companies, quickly evaluated and fast-track registered four alternative post-emergence herbicides:

- clodinafop
- fenoxaprop
- sulfosulfuron
- tralkoxydim.

These herbicides, all of which provide effective control of *Phalaris minor*, were recommended in 1997 and the recommendation on isoproturon was withdrawn. While the speedy release of these replacement herbicides once again brought the *Phalaris minor* infestation under control and restored yields to their previous level, this was recognised as a short-term and incomplete solution for two reasons.

- Inevitably, the continued use of new herbicides as the sole method of weed control will result in the re-emergence of chemical resistance.
- The new herbicides are expensive, which in turn will affect their rate of adoption, level of use and profitability of wheat growing.
  - Herbicide costs increased from Rs450/ha (isoproturon) to Rs1500–1800/ha (new chemicals)—a fourfold increase.
  - Use of the new chemicals is delivering a yield improvement of up to 1000 kg/ha over the yields with resistance to isoproturon. This is worth an additional Rs5000/ha in wheat income, a return of Rs3 for each Rs1 spent on new chemicals. Despite this, many farmers were, at least initially, extremely reluctant to adopt the new chemicals.

It became apparent that a new paradigm for weed control was needed—one that would provide a sustainable, long-term control solution in a way that was commercially attractive to farmers.

3 The ACIAR project

The sequence of events which led to the ACIAR project is set out in Table 2.

Table 2. Key events leading to the ACIAR project

Date	Event
Early 1993	Herbicide resistance of *Phalaris minor* confirmed by R.K. Malik and colleagues
November 1993	International workshop (organised by R.K. Malik and colleagues on behalf of the Indian Society of Weed Science) to discuss the herbicide resistance issue Key Australian weed scientists and other foreign experts attend
May 1994	Involvement of Haryana Agricultural University (HAU) and Punjab Agricultural University (PAU) together with support from the International Maize and Wheat Improvement Center (CIMMYT) rice–wheat consortium for the Indo-Gangetic Plains Project proposal submitted to ACIAR
July 1996	Research commenced under ACIAR project (one year ahead of funds)
July 1997	ACIAR project funding commences

In retrospect, in terms of the solutions that have emerged, key aspects of the events in Table 2 were:

- the involvement of Australian weed scientists, with their extensive Australian experience in finding solutions to herbicide resistance;
- the involvement of the International Maize and Wheat Improvement Center (CIMMYT), with its long experience in researching zero tillage systems and endeavouring to get them adopted in South Asia;
- the preparedness of ACIAR, CIMMYT, HAU and Punjab Agricultural University (PAU) to collaborate strongly to find a solution; and
- financial contributions made by AusAID.

Australian scientists are acknowledged leaders in herbicide resistance of weeds and in determining how best to respond to achieve long-term sustainable weed control. Sustainable responses are based around integrated packages. These combine herbicides with management systems that exploit a knowledge of weed ecology to reduce the seed bank and its ability to germinate. This total weed management approach minimises, but does not eliminate, the use of chemicals. The effective life of chemicals can be greatly extended and the reliance on herbicides greatly reduced as weed seed bank density is progressively reduced.

What the ACIAR project involved

The ACIAR project had a number of dimensions (Figure 2).

Figure 2. Dimensions of the ACIAR project

- Identify and survey the nature and magnitude of resistance to *Phalaris minor*
- Field studies to investigate:
  - effectiveness of chemical alternatives to isoproturon
  - effectiveness of various non-chemical methods of weed control (raised beds, alternative crops, inter-row cultivation, delayed sowing etc.)
- Identify wheat genotypes with superior competitive ability against weeds (essentially an Australian component of the project)
- Extend (via a farmer/private farm participatory approach) information on weed resistance management to Indian scientists, field workers, extension agents, farmers
- Develop resistance management expertise in India through conduct of project in India and staff training in Australia and Mexico

Project achievements

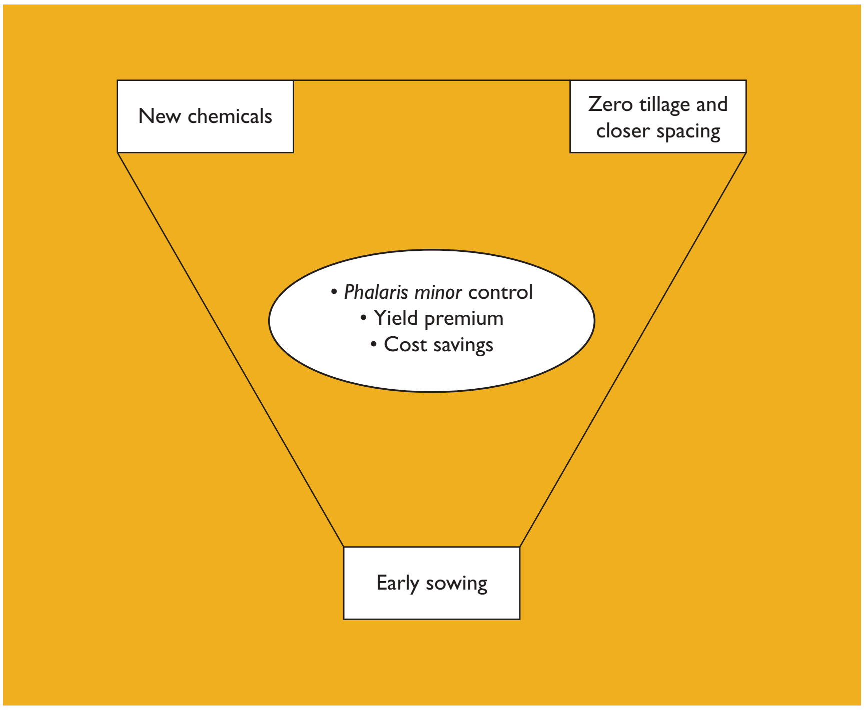
Earlier ACIAR-commissioned reviews concluded that the project has delivered on all its objectives.

- The *Phalaris minor* chemical resistance problem has been carefully analysed and surveyed.
- Effective chemical alternatives to isoproturon have been identified and registered.
- An environmentally sustainable and highly profitable weed management system (centred on zero tillage combined with new chemicals) has been formulated.
- A high rate of adoption of this system has been achieved through engaging and empowering farmers at each stage of the research.
- The Indian weed scientists involved now have an international reputation for their achievements and expertise in weed resistance management.

- The project has made a start on evaluating the ability of different wheat genotypes to outcompete weeds, but this is very much 'work in progress'. Delivering varieties with an enhanced ability to outcompete weeds remains a long-term objective.

The integrated approach to weed control that has emerged from the project and is now being widely adopted by farmers consists of four interconnected components (Figure 3).

Figure 3. Integrated package for *Phalaris minor* weed control



The new chemicals

Work on identifying and fast-track registering the new chemicals was essentially complete before the ACIAR project. The credit for this work belongs to HAU–PAU weed scientists working in cooperation with the chemical companies. The result is a range of highly effective (though high cost) new herbicides whose use, when combined with the agronomic components of the package developed later, can be reduced over time as the *Phalaris minor* seed bank becomes progressively smaller.

Zero tillage and closer spacing

The most spectacular achievement of the project has been to bring about the widespread adoption of zero tillage as a key component of the *Phalaris* *minor* control package. Zero tillage involves placement of the seed into the soil using a seed drill without prior soil preparation.

The concept of zero-till agriculture has been around for a long time. Its potential benefits, in terms of reduced damage to soil structure and savings in cultivation costs, are well known to agricultural scientists. Achieving adoption, however, requires overcoming the longstanding farmer belief that more rather than less tillage yields better crops.

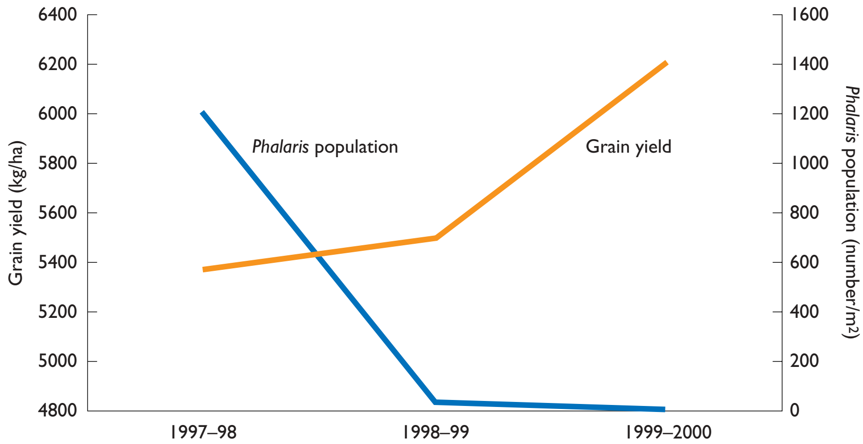
Zero-till technology was experimented with in north-western India in the 1970s at PAU, but failed to interest farmers. In part this was due to the lack of suitable implementation equipment at the time. Zero tillage was also introduced into the rice–wheat system in Pakistan in 1983 by CIMMYT using a New Zealand seed drill. In both cases the motivation was not weed control. In fact, at the time, agronomists did not realise that zero tillage would reduce grassy weed emergence.

In the early 1990s, zero tillage was again on the agenda in the search for methods to overcome the *Phalaris minor* infestation problem. CIMMYT, with funding from the United Kingdom's Department for International Development (DFID), undertook a project on zero-till technologies. Drills were purchased from CIMMYT's DFID project money and used as part of HAU's work under Dr Malik for field trials with and by local farmers as part of the ACIAR project.

The hypothesis behind the use of zero tillage was that savings in land preparation costs could be used by farmers to fund the new expensive chemicals for *Phalaris minor* control following the demise of isoproturon. The trials demonstrated the link between zero tillage and reduced grassy weed emergence. There was much greater *Phalaris minor* control in zero-till plots. By combining zero tillage with the new herbicides, it was demonstrated that *Phalaris minor* infestation could be almost eliminated after three to four years (Figure 4). The enhanced weed control and savings in cultivation costs were achieved with no reduction in wheat yields. In fact, yields increased as the weed problem diminished and wheat germination was improved.

Less water was needed for the first irrigation through retention of the water in the soil from the previous rice crop. With zero tillage, the crop remains green after the first irrigation because the water runs quicker through the soil. By contrast, with conventional tillage, the crop is pale yellow after the first irrigation due to prolonged water stagnation. Water savings to farmers are estimated by Singh et al. (2002) at around 28% in the first irrigation, and crops exhibited less lodging.

Figure 4. Continued use of zero tillage rapidly reduces the *Phalaris minor* population (results for two permanent sites in Kaithal district) (data source: Malik et al. (2002), p. 13)



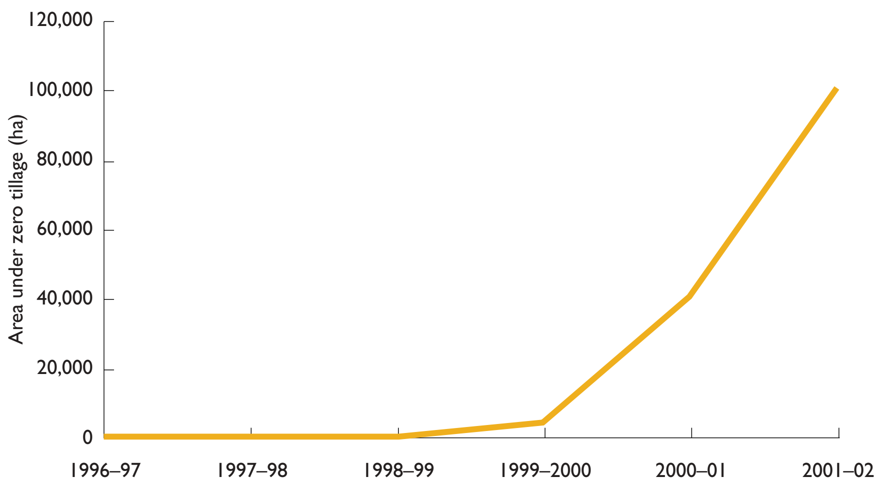
Under zero tillage, rice straw residue is incorporated into the soil while creating minimum disturbance. Soil physical, chemical and biological properties are improved. Increased carbon storage has beneficial agronomic effects quite apart from greenhouse gas considerations. Soil temperature is raised in the cooler part of the year and lowered in the hotter part, enhancing crop growth.

Zero tillage is now being rapidly adopted in rice–wheat cropping systems of north-western India (Figure 5). The ACIAR project, by providing funding and scientific support to HAU–PAU to support the work of Dr Malik's group, together with the support of CIMMYT, played an important role in the field trial work which resulted in farmer acceptance and rapid adoption of zero-till technology.

The adoption of zero tillage has necessitated the development of a local manufacturing company of suitable direct drill equipment. Project personnel have played an active role in this. In India, there are currently 12 recognised manufacturers of suitable drills and more than 3000 drills are currently being used. Production capacity should be able to supply the big increase in machines required over the next few years as adoption of zero tillage rapidly increases.

Project research has shown that modifying the zero-till drills to give closer spacing of the seed (to 15 cm rather than the 22.5 cm spacing on conventional drills) gives better weed control through higher tillering of the wheat.

Figure 5. Adoption of zero tillage has been spectacular in Haryana (data source: Malik et al. (2002))



Early sowing

To maximise yields, wheat must be planted at the optimal time. Planting late reduces the efficiency of crop response to fertilisers and reduces yields. Under conventional tillage, there is a long turnaround between harvest of the rice crop and wheat planting through the time taken to do six to eight cultivations. Zero tillage has enabled farmers to sow wheat earlier—by up to two to three weeks. Experiments have shown a 1–1.5%/day reduction in yield in Haryana for each day planting is delayed beyond early November (Figure 6). Singh and Kumar (2002) report yield losses of 30 kg/day/hectare through late planting of wheat in Haryana and Punjab.

Project expenditures

The project received funding from ACIAR and AusAID, from the University of Adelaide as commissioned organisation, from HAU and PAU as developing country partners, from the rice–wheat consortium (RWC) of CIMMYT, and from the Herbicide Resistance Action Committee. Estimates of funds spent, including in-kind contributions from each organisation, are shown in Table 3. Although the ACIAR project funding did not arrive until 1997–98, considerable work was done in the two years before this by HAU and PAU personnel, supported by the RWC of CIMMYT and by state government funds in India. Some of the figures in Table 3 are estimates. Only the ACIAR figures can be validated against records of what was actually spent.

Figure 6. Early sowing means higher yields (1998–99 wheat crop, Haryana) (data source: Malik et al. (2002), p. 18)

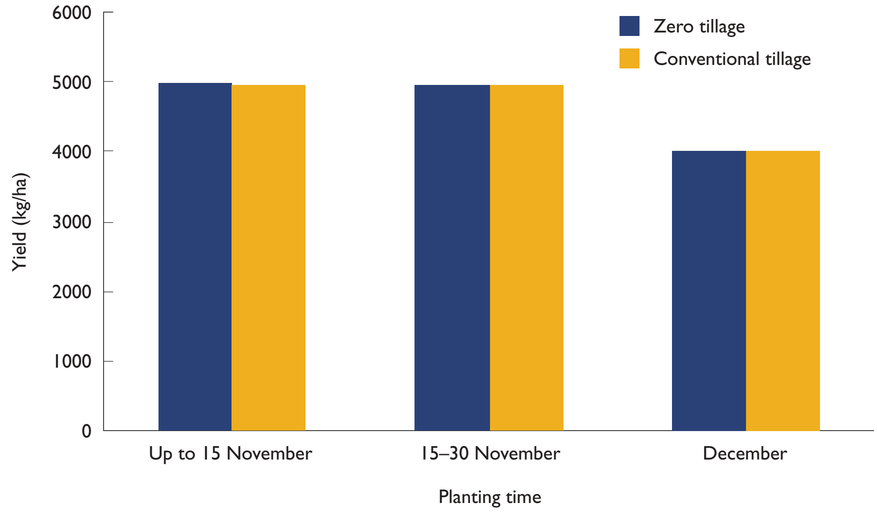


Table 3 indicates around $1.1 million of expenditure in cash and in kind over the life of the project by the organisations involved (equivalent to $1.3 million in 2000–01 dollars). Further support, mainly in kind, was given by other organisations—such as Cornell University in the United States of America with assistance on herbicide application methods.

Table 3. Estimated project expenditure (A$)

Supplier	1995–96	1996–97	1997–98	1998–99	1999–2000
ACIAR-managed component			170,425	133,924	115,742
Commissioned organisation (University of Adelaide)			67,400[a]	67,400[a]	67,400[a]
Developing country partner (HAU–PAU)[b]	31,360[c]	31,360[c]	31,360[a]	31,360[a]	31,360[a]
RWC–CIMMYT[d]	90,000	50,000	53,200	60,000	60,000
Herbicide Resistance Action Committee	11,000	11,000			
Total	132,360	92,360	322,385	292,684	274,502

[a] *These are the amounts that these organisations agreed to contribute (in cash and in kind) at project commencement.*
[b] *HAU–PAU = Haryana Agricultural University– Punjab Agricultural University.*
[c] *The same level of contribution from state government funds is assumed for the two years before commencement of the ACIAR project.*
[d] *Estimate of cash and in-kind contribution based on discussions with Peter Hobbs of the rice–wheat consortium of the International Maize and Wheat Improvement Center (RWC–CIMMYT).*

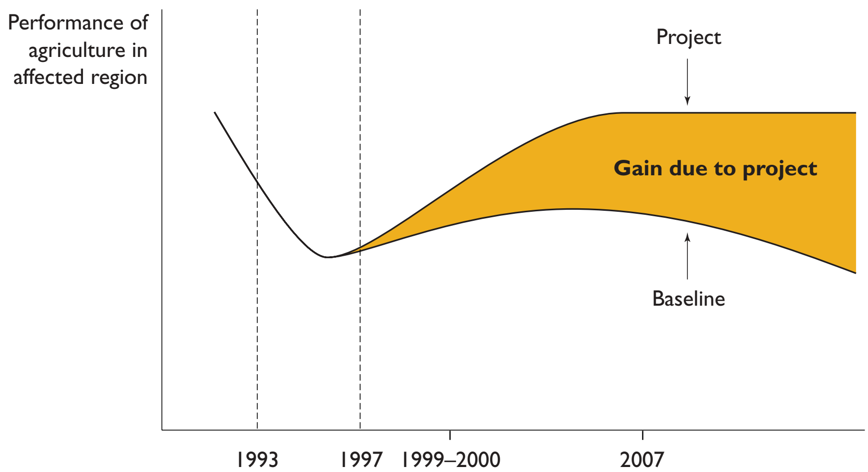
4 Evaluating the economic gains

The ACIAR project was very much a team effort. Achievements were the outcome of collaborative research and extension by key personnel from HAU, PAU, CIMMYT and the University of Adelaide. ACIAR project funding was instrumental in ensuring this team had adequate resources to do the job.

We first focus on the value of the economic gains from the project as a whole. How much credit ACIAR can take for these gains compared with the credit due to other contributors is a more difficult and perhaps less meaningful question, which we consider later.

We measure the benefits from the project relative to a baseline reflecting anticipated outcomes assuming no project. How we specify the baseline is thus critical. The difference between the baseline and the actual outcome represents the gain due to the achievements of the project (Figure 7).

Figure 7. Schematic representation of project gains to be measured



The baseline shows a deteriorating agricultural performance in the region in the early 1990s due to the emergence of herbicide resistance in *Phalaris minor*. There is a slight improvement in 1997 with the release of new chemicals, but adoption is initially poor because of their high cost. In addition, the area covered by chemical resistance continues to spread. By 2007, agricultural performance is projected to decline even further as resistance to the new high-cost chemicals becomes apparent. The development of resistance is due to the new chemicals being used as the sole agent for weed control.

The baseline recognises that the release of the new chemicals and the reversal of the yield losses due to *Phalaris minor* infestation following chemical resistance to isoproturon happened independently of the ACIAR project, though the project did contribute some support for their testing. But zero tillage is not part of the baseline. The adoption of zero tillage through demonstration trials undertaken as part of the search for an effective weed control package is viewed as a major achievement of the team which ACIAR project funds helped support.

The project line shows a rapid recovery in agricultural performance in the region commencing in year 1999–2000, the first year of uptake of zero tillage by farmers. Agricultural performance accelerates rapidly in the following years in line with the actual and projected uptake of zero tillage, closer spacing and early sowing.

The gap between the baseline and project line, appropriately valued, represents the economic contribution of the collaborative project. It is this gap that we measure.

Components of gains

The gap between the baseline and project line in Figure 7 can be partitioned into eight components of gains (Table 4). Not all these components can be quantified. We make the following assumptions.

a. Prevention of future decline in yield through re-emergence of herbicide resistance

We assume that, if not for the achievement of the project in designing an integrated approach to weed control that is only partially dependent on herbicides, the herbicide-resistance story of the early 1990s would repeat itself by 2007. We assume that:

- by 2007, 50,000 hectares (Haryana plus Punjab) would have a serious *Phalaris minor* reinfestation;
- the area of serious infestation would escalate rapidly to peak at 1.16 million hectares by 2014, by which time it would encompass 70% of the 1 million hectares of wheat–rice cropping system in Haryana and 20% of the 2.3 million hectares of wheat–rice cropping system in the Punjab (Table 5); and
- the average yield decline on infested land would be 1.35 t/ha.

Table 4. Components of economic gains

Component	Justification
Prevention of future decline in yield through re-emergence of herbicide resistance	Under the baseline, continued use of the new chemicals is likely to see herbicide resistance re-emerge on a serious scale within ten years (by 2007). The yield declines experienced in the early 1990s will be repeated. By using these chemicals judicially as part of a long-term sustainable package with zero tillage, chemical resistance is unlikely to re-emerge.
Reduction in herbicide outlays	Use of the new herbicides in the baseline must continue at the same cost per hectare each year (until chemical resistance renders the herbicides ineffective). But, by combining the new herbicides with the zero-till package, *Phalaris minor* seed banks are rapidly reduced to negligible levels after four years of zero tillage. Herbicide costs to achieve control can therefore be progressively reduced.
Reduction in tillage costs	Conventional tillage involving six to eight workings is reduced to one working under zero tillage.
Avoidance of long-term yield decline through gradual degradation caused by conventional cultivation	Adoption of zero tillage will arrest and eventually reverse any long-term damage to soil structure and soil health through conventional cultivation methods. Achievement of environmental sustainability should deliver a small yield dividend. There will also be water savings, but these have no commercial value at present.
Yield premium through early sowing and closer spacing	With zero tillage providing opportunities for early sowing allowing more time for crop maturity, a yield premium of around 1% per day for seven to ten days is likely.
Capacity building/training	The project has resulted in a greater capacity of Indian weed scientists to monitor and respond to future changes in the performance of the rice–wheat cropping system. Such changes, which may involve weed shifts and yield shifts, are inevitable.
Improved environmental outcomes	Zero tillage will mean savings in greenhouse gas emissions and savings in water use.
Prospect of more weed-competitive varieties in the long term	The work on evaluating wheat genotypes for resistance to competition from weeds may lead to superior varieties over the longer term.

b. Reduction in herbicide outlays

We assume that, relative to baseline, expenditure on the new herbicides will continue at the same rate for the first four years of zero tillage. This represents outlays of Rs1500 to Rs1800/ha. After the fourth year, we assume that average annual expenditures on herbicides can be reduced by Rs450/ha and still maintain effective weed control.

The expenditure saving only applies to the area sown with zero tillage. All areas that maintain conventional tillage will continue to incur the same herbicide outlays per hectare as in the baseline. We assume that the uptake in Haryana will be particularly rapid over the next few years driven by the big cost savings. Zero tillage uptake will peak at 920,000 ha in 2006–07, by which time 80% of the wheat–rice region of Haryana will have adopted it (Table 6). In Punjab, we have assumed a much lower uptake of zero tillage with a peak adoption of only 120,000 ha by 2006–07. In Punjab, the incidence of *Phalaris minor* resistance to isoproturon was much lower than in Haryana and large areas appear to have remained unaffected. Isoproturon is still used in these areas. In addition, our assumptions recognise the much stronger mindset of Punjab farmers for a clean field (as delivered by conventional cultivation) before sowing.

Table 5. Assumptions about the area affected by re-emergence of herbicide resistance

Year	Area affected (ha)[a]
2007	50,000
2008	100,000
2009	200,000
2010	400,000
2011	800,000
2012	900,000
2013	1,000,000
2014–2030	1,160,000

[a] *Average yield decline of 1.35 tonnes/ha on area affected*

These projections of zero tillage uptake are, by nature, speculative. They may well, however, prove pessimistic, particularly in the Punjab in view of the big cost savings available. In addition, they do not take into account adoption in states other than Haryana and Punjab. In South Bihar and Uttar Pradesh, for example, there are large areas of rice–wheat that may well adopt zero tillage in the light of the demonstration effect from the ACIAR project. But adoption in areas outside of Haryana and Punjab will be driven more by the contribution of zero tillage to profits rather than as an integrated weed control package. Malik et al. (2002, p. 20) consider that zero tillage is likely to have the greatest impact in the eastern part of India where sowing of wheat is invariably delayed. And adoption of zero tillage is proceeding in Pakistan in areas which have not had a *Phalaris minor* problem.

c. Reduction in tillage costs

A range of recent studies report cost savings from zero tillage on farms in Haryana (Nagaragan et al. 2002; Sharma et al. 2002a,b). In addition, comments by farmers participating in zero tillage trials with HAU agronomists—reported in Malik et al. (2002)—provide a rich source of information on their cost savings from zero tillage and their opinions of its value (Table 7). Estimates of cost savings vary from Rs1400 to Rs2500/ha. Diesel consumption is reduced by between 60 to 80 L/ha. Cost savings of

Rs2000/ha are assumed to be achieved on the projected area of zero tillage shown in Table 6.

Table 6. Reduction in expenditure on herbicides relative to baseline

Year	Area of zero tillage	Reduction in herbicide expenditure	Yield premium (avoidance of long term yield decline)		Yield premium due to early sowing
	(ha)	(Rs)	(ha)	(kg/ha)	(kg/ha)
1997	0	0			150
1998	2000	0			150
1999	8000	0			150
2000	40,000	0			150
2001	100,000	2000 × 450			150
2002	180,000	8000 × 450			150
2003	350,000	40,000 × 450			150
2004	600,000	100,000 × 450			150
2005	800,000	180,000 × 450			150
2006	920,000	350,000 × 450			150
2007	920,000	600,000 × 450	2000	20	150
2008	920,000	800,000 × 450	8000	20	150
2009	920,000	920,000 × 450	40,000	20	150
2010	920,000	920,000 × 450	100,000	20	150
2011	920,000	920,000 × 450	180,000	20	150
2012	920,000	920,000 × 450	350,000	20	150
2013	920,000	920,000 × 450	600,000	20	150
2014	920,000	920,000 × 450	800,000	20	150
2015–30	920,000	920,000 × 450	920,000	20	150

Source: CIE estimates

d. Avoidance of long-term yield decline through adverse effects of conventional tillage

Singh and Kumar (2002) report significant economic losses from soil degradation in Haryana and Punjab (Rs3700 to Rs5400/ha). They estimate that degraded land represents 22% of the sown area of Haryana and 37% of Punjab.

Conventional cultivation methods in the rice–wheat belt are particularly hard on soil structure. Effects, in terms of reduced crop yields, are hard to isolate because of the very gradual impact over a long term and the numerous other more visible influences on yield from year to year. Deteriorating soil structure and fertility through conventional cultivation is viewed as one reason for the levelling off of crop yield increases over time in north-western India.

Table 7. Farmer views on zero tillage[a]

Farmer	Effects on weed germination	Cost savings (Rs/ha)	Yield	Other
1	Reduces germination	2000–2500		
2		Significant	Equivalent to conventional sowing	
3	Reduces weed infestation	Saves money and time		
4		2000–2250	Increase of 750–1000 kg/ha	Crop can be sown 9–10 days earlier
5		Saves time, machinery and implements, and diesel	Higher yield	
6	Improved weed control through full germination of wheat	2500	Yield increase	
7	No germination	Time saving	Yield increase	Less crust formation
8	Reduced germination	875	Yield increase	Sowing can be done 5–7 days earlier
9	Reduced germination	2000–2250	Yield increase of 500–1000 kg/ha	Sowing possible 7–10 days earlier
10	Less *Phalaris minor*	Significant	Yield increase	Reduced lodging, water savings
11	Improved weed control through faster and more conventional germination of wheat	1000	Yield increase of 700–800 kg/ha	Sowing completed 5 days earlier. Faster germination and no crust formation
12	Reduces weed germination	3000	Yield increase	
13				Very good
14			Has proven 'more plough and more eat' to be wrong	
15		Saves time, reduces tractor maintenance, saves diesel		Water does not stagnate
16		Saves water, electricity, diesel, time		
17		Less expenditure, time	200 kg/ha	
18		Less expenditure	Increase	Early sowing
19	Decrease	Saves labour, time and water	Increase	
20		Reduced expenditure on diesel	Increase	Reduced lodging

Continued on next page

Table 7. Farmer views on zero tillage (cont'd)

Farmer	Effects on weed germination	Cost savings (Rs/ha)	Yield	Other
21		Saves diesel, time, tractor maintenance		Reduced lodging
22	Better weed control	Saves diesel	Better due to early sowing	Excellent germination, less lodging
23	Controls weeds	Saves time		Helps maintain soil quality
24	Less germination	1500–1750 in diesel	500 kg/ha increase	Crop remains green
25	Less germination	Saves time, expenditure	Higher	Crop remains green
26		1250 in diesel	700–800 kg/ha increase	Crop does not turn yellow after first irrigation
27		2000	200–300 kg/ha increase	Crop remains green
28		1750 in ploughing costs	500–750 kg/ha increase	No lodging, crop green and healthy
29		2000		No lodging, crop does not turn yellow
30		1000 in diesel	250–500 kg/ha increase	Water does not stagnate and crop does not lodge
31		1250 in diesel	500–750 kg/ha increase	No lodging and no yellowing
32		1250 in ploughing	500–750 kg/ha increase	No lodging and no yellowing
33	Less *Phalaris minor*	1250 in ploughing	Increase	Crop does not lodge, earheads long and thick
34	Reduced weeds	Less time and money	Increase	Reduced lodging
35		Saves time	800–1000 kg/ha	Crop not damaged after first irrigation
36	Less *Phalaris minor*	1500–1750 in ploughing costs	500–750 kg/ha	Water does not stagnate and crop does not turn yellow
37	Less germination	1750 in ploughing costs	Increase	
38	Reduced *Phalaris minor*	2000 in ploughing costs	Increase	More water infiltration and crop remains green
39		1000–1350 in diesel		DAP[b] placement better
40		2000–2250	Increase	Crop remains green
41		1750–2000	Increase	Crop remains green
42	Less *Phalaris minor*	1250	Increase	Reduced lodging and increased infiltration
43		1500–1750	500–1750 kg/ha	Water does not stagnate, crop does not yellow
44	Less germination	Saves labour, time	Increase	
45	Less germination	1000 in ploughing	Increase	Sowing completed five days earlier

Continued on next page

Table 7. Farmer views on zero tillage (cont'd)

Farmer	Effects on weed germination	Cost savings Rs/ha)	Yield	Other
46	Good control	Saves money	Increase	
47	Reduced weeds	3000	Increase	
48		Saves time	700 kg/ha increase	
49		Saves time and water		Excellent
50	Reduced germination	Saves time, money	Increase	Easier irrigation
51	Less germination	Saves time, diesel, water		
52		Saves time, water cost		
53	Reduced germination	2500		
54			Increase	Less loading
55		1750		Correct placement of DAP[b]
56		2250		
57		Saves diesel, time		
58		2250–500		Land remains levelled
59		2500	Increase	Early sowing, no crust formation, less water at first irrigation
60	Less germination	2500		
61		Saves time, diesel		

[a]*These are the views of 61 innovative farmers collaborating with university scientists in zero-till trials.*
[b]*DAP = di-ammonium phosphate, a fertiliser.*
Data source: Malik et al. (2002).

We assume that as a result of the adoption of zero tillage, a small yield dividend of 20 kg/ha relative to baseline (around 0.5% of current yields) will be apparent after ten years of zero tillage and will continue through to 2030.

e. *Yield premium through early sowing and closer spacing*

With the adoption of zero tillage, the time taken between rice harvest and wheat sowing can be shortened considerably. Singh and Kumar (2002) estimate that late planting of wheat occurs on 20% of the rice area in Punjab and 40% in Haryana, which reduces the wheat yield by 30 kg/ha/day. Other estimates are that yield increases of 1% per day for up to seven to ten days are achievable through early sowing. We assume a yield increase relative to baseline on the area of land sown with zero tillage equipment (at 15 cm rather than the conventional 22.5 cm spacing) of 150 kg/ha.

f. Capacity building/training

An important outcome of the project has been training and capacity building. Eight Indian weed scientists have received training at the University of Adelaide and CIMMYT. Indian weed scientists, through their collaboration with Australian and other experts, are now better equipped to put together holistic solutions (which extend well beyond the conventional heavy reliance on herbicides) to future weed management problems. This should assist in avoiding future sustained losses from weed infestation. We do not compute a value to the capacity building and training components, though acknowledge that this value may well be significant.

g. Improved environmental outcomes

In addition to the yield dividend likely from a reversal of the slow degradation of soils under conventional tillage, zero tillage is also likely to deliver several other environmental benefits. The reduction in diesel consumption of 60 to 80 L/ha represents a reduction of 0.25 t of carbon dioxide emissions into the atmosphere. There may also be gains through less carbon oxidation during cultivation and perhaps some carbon sequestration through incorporation of residue into the soil, though these gains have not yet been quantified. A reduction in atmospheric carbon dioxide emissions may have long-term environmental benefits. It may also be commercially valuable in the event that a carbon tax or emissions trading system is implemented on a global scale. But at this stage of global greenhouse gas policy development it has zero commercial value.

Another potential environmental and commercial benefit comes from the saving in water use under zero tillage at the first irrigation. This saving could be as high as 5% per year. Water is not currently priced to farmers so the savings from lower water use are not a commercial consideration. But this situation could change, especially if the watertable keeps on falling.

We have not included any financial benefit for the improved environmental outcomes likely from reduced carbon dioxide emissions and reduced water use.

h. Prospect of more weed-competitive varieties in the long term

The ACIAR project has made an important start to evaluating the competitive ability of wheat cultivars against grassy weeds. This knowledge, may in the longer term, lead to the release of improved varieties for farmers. At this stage, development of more weed-competitive cultivars remains work in progress. We do not incorporate any gains into the analysis.

Projection horizon

A feature of the solution package to the *Phalaris minor* infestation problem is its long-term sustainability. There is no reason why the gains should not persist well into the future. We assume a pay-off horizon of 30 years commencing in 1999–2000. Because of the discount rate (a 5% rate is used), pay-offs beyond this period have only a small present value.

Gains to India and gains to Australia

A requirement of ACIAR project evaluations is that the economic gains be computed for both the country collaborator (India) and for Australia. For this project, all economic gains in the short term accrue to India.

Over the longer term, the work on evaluating the ability of different wheat genotypes to out-compete weeds may yield benefits to wheat growers in Australia as well as in India.

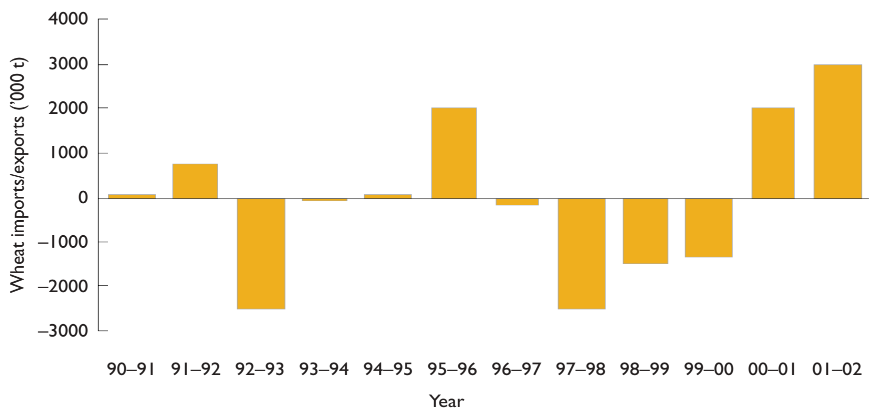
Valuing the gains

The gains specified above are in terms of cost savings and yield increases. These gains need to be valued at so-called shadow prices—the prices that would operate in the absence of subsidies—rather than the actual or subsidised prices in the Indian economy.

The Indian government runs a farm support price (procurement price) system for wheat and many other commodities. High procurement prices and favourable growing seasons in recent years have encouraged a big increase in India's wheat production—from 55.1 million tonnes in 1990–91 to 78.6 million tonnes in 1999–2000. Large stocks of grain have accumulated—current grain stocks exceed 70 million tonnes, one third of which is wheat. India has turned from a net importer to a net exporter of wheat (Figure 8). Imports of wheat are subject to a tariff of 50%.

India is now exporting wheat on a significant scale. Because of real and perceived quality problems, India's wheat exports are discounted relative to ruling free on board (f.o.b.) prices. The discount over the 1990s ranged from 3 to 34% (Chand and Jha 2001, p. 45). According to United States Department of Agriculture estimates, the Indian government in mid-2001 was offering wheat to government trading houses, contingent on it being exported at less than two thirds the price of procurement, which amounts to a subsidy of US$32/t. This in turn has drawn complaints from World Trade Organization member countries. Australia, as a major exporter of wheat, has lost sales in the Asian region to subsidised Indian wheat exports.

Figure 8. Indian wheat trade (data source: United States Department of Agriculture statistics)



The current procurement price of wheat to farmers is Rs6100/t. This compares with an f.o.b. export price for US no. 2 hard red winter wheat (Gulf) (considered by Indian economists to be the appropriate indicator price) of around US$130/t. After allowing for a 20% discount to the world price and taking into account transport costs from the farm to the wharf, we consider the economic price of Indian wheat to be around Rs4800/t.

India also provides input subsidies to agricultural and other activities. In wheat growing, the main subsidies are on fertilisers, electricity and canal irrigation. Rates of subsidy peaked in the mid-1990s, but are now declining as governments seek to reduce the financial burden. The input subsidy story for Indian agriculture is a complex one. Acharya (2001, p. 195) argues that the subsidies are, to some extent, there to overcome inefficiencies (implicit taxes) on input-supplying industries. For example, a large proportion of the fertiliser subsidy goes to the fertiliser industry and its feedstock-supplying agencies, and electricity subsidies compensate for inefficient transmission and distribution systems in state-owned electricity enterprises. And for canal irrigation projects, costs are inflated by bad design and arrangement. For these reasons, actual subsidies accruing to farmers are believed to be much lower than what is generally projected. We therefore do not adjust the farm cost savings for subsidies.

Production response

Indian farmers can be expected to respond to the improvement in their profitability from the cost reductions and yield increases associated with zero tillage, closer spacing and earlier sowing. Chand and Jha (2001, p. 73) report a supply elasticity of 0.43 for Indian wheat farmers nationwide. The elasticity for farmers operating in a rice–wheat rotation in these circumstances is likely to be a lot lower than this. Our analysis incorporates a significant production response through the rapid adoption profile for zero tillage. An additional response might be expected through farmers intensifying their use of inputs, particularly fertiliser. But wheat growers in the region have already reached sharply diminishing returns to further intensification with conventional inputs (Prabhu and Heisey 2001). For this reason, we use a low supply elasticity of 0.1.

Distribution of gains between producers and consumers in India

The production response to the reduction in unit costs and the yield increases will result in more wheat produced and higher profits for farmers adopting zero tillage. In an undistorted wheat pricing policy environment, some of the benefits could be expected to flow through to Indian wheat consumers as lower prices for wheat. But the policy environment is highly distorted through the procurement pricing system and by a complex set of government agency interventions in the domestic wheat market.

The Food Corporation of India (FCI), a government agency, purchases all wheat offered by producers at the minimum support price. The FCI runs a buffer stock scheme for wheat, partly motivated by concerns for food security, to ensure stable and affordable prices to consumers. This wheat is then sold to consumers under the public distribution scheme at so-called issue prices, which depend on whether the consumer is above or below the poverty line. Sales are heavily subsidised to low income consumers. Different prices are also set to different millers depending on location.

In this policy environment, the increased wheat supplies will not lead to a reduction in wheat prices to domestic consumers. Indian households will suffer a reduction in welfare through the need for the government to fund, through higher taxes or reduced outlays on other activities, a greater volume of subsidised wheat production. This consumer welfare loss needs to be taken into account to arrive at an estimate of the net benefit to the Indian economy from the project.

Results

The profile of producer gains from each component is set out in Table 8. These gains are valued at world rather than domestic prices so they are net of the increase in consumer subsidies needed to support the additional wheat production.

Table 8. Components of producer benefits (A$m)[a]

Year	Prevention of yield decline	Reduction in herbicide outlays	Reduction in tillage costs	Avoidance of long-term yield decline through degradation	Yield premium due to early sowing and closer spacing	Total producer gain
2000–01	0.0	0.0	3.2	0.0	0.0	3.2
2001–02	0.0	0.0	8.0	0.0	0.0	8.0
2002–03	0.0	0.1	14.4	0.0	0.0	14.5
2003–04	0.0	0.7	28.0	0.0	0.0	28.7
2004–05	0.0	1.8	48.0	0.0	0.0	49.8
2005–06	0.0	3.3	64.0	0.0	0.0	67.2
2006–07	0.0	6.3	73.5	0.0	0.0	79.9
2007–08	0.6	10.8	73.5	0.0	54.1	139.1
2008–09	1.2	14.5	73.5	0.0	54.1	143.3
2009–10	2.3	16.6	73.5	0.2	54.1	146.8
2010	4.6	16.6	73.5	0.4	54.1	149.3
2011	9.3	16.6	73.5	0.7	54.1	154.2
2012	10.4	16.6	73.5	1.3	54.1	156.0
2013	11.6	16.6	73.5	2.3	54.1	158.2
2014	13.4	16.6	73.5	3.1	54.1	160.8
2015–2030	13.4	16.6	73.5	3.5	54.1	161.2

[a]*Increase in gross margins at world prices. Hence is net of additional consumer subsidies to support the higher production.*
Data source: CIE calculations.

The largest component of benefits is the reduction in tillage costs followed by the yield premium from early sowing. Prevention of future yield declines by avoiding the re-emergence of chemical resistance involves a significant ‘first round’ benefit. But the yield declines would turn wheat growing from profit into loss necessitating a switch to other crops. Taking this switch into account reduces the ‘final round’ benefits from this component.

The present value of the future stream of benefits (valued at world prices) over a 30-year horizon comes to $1809 million in year 2000–01 in present value terms (Table 9). This is made up of $2678 million of producer benefits valued at domestic prices, less $869 million of additional consumer subsidies associated with the expanded wheat production.

Allocation of benefits between ACIAR and other contributors

The success of this project owes much to synergies and teamwork—contributed from individuals with different backgrounds and from different institutions, but with a common interest in the problem of herbicide resistance and how to overcome it. The initial (short-term) solution, the release of new chemicals, was derived independently of the ACIAR project. The key component of the longer-term solution (zero tillage) was also conceived and tested independently of the ACIAR project and involved many people from different organisations.

But, until the project, adoption of zero tillage was negligible. It was a great idea waiting for a trigger for it to be adopted. The high cost of the new chemicals provided that trigger. And the extensive trials of zero tillage conducted for farmers and by farmers, which were made possible by the ACIAR project support, proved critical to overcoming the scepticism of farmers to adoption.

For these reasons, the issue of how much of the gains are attributable to the ACIAR project is a difficult one to address. Each contributor clearly needed the other for eventual project success.

The component of gain represented by the avoidance of resistance to new herbicides can be clearly allocated to the ACIAR project, which brought Indian weed scientists in direct contact with the ideas and experiences behind the integrated approach to weed management used in Australia. But to achieve this gain requires the adoption of zero tillage.

Zero tillage is clearly a profitable technology by itself. It does not need a weed problem to justify its introduction. So it seems reasonable to assume that zero tillage would eventually have been introduced without the ACIAR project—though with a delay.

We assume that, without the ACIAR project, zero tillage would have been introduced to the region, but with the adoption profile lagged by three years. This assumption is consistent with the observation of zero tillage now starting to be adopted in other parts of the rice–wheat system in South Asia that have not had a *Phalaris minor* weed problem. On this basis, we calculate gains that can be attributed to ACIAR's support role of

$238 million (Table 10). With the cost of the ACIAR-funded project amounting to only $1.3 million (in 2000–01 dollars), this yields a benefit–cost ratio of around 180:1. The sensitivity analysis in Table 10 shows that these gains would be much higher if the ACIAR projects effects were to advance the adoption profile of zero tillage by more than three years.

Table 9. Summary of benefits and costs (net present value[a] to 2030)

Producer benefits[b]	Net present value	
	(A$m)	(%)
Prevention of future decline in yield through re-emergence of herbicide resistance	103	5.7
Reduction in herbicide outlays	175	9.7
Reduction in tillage costs	950	52.5
Avoidance of long-term yield decline through degradation	24	1.3
Yield premium due to early sowing and closer spacing	557	30.8
Total producer benefit (world prices)	1809	100.0
Net gain to India	**1809**	

[a] *Discount rate of 5%.*
[b] *Increase in gross margin valued at world prices.*
Data source: CIE calculations.

While the results of the assessment are clearly sensitive to assumptions on when zero tillage would have been adopted by farmers without the ACIAR project, the key point is that ACIAR has played a vital role in a very successful project.

Table 10. Net benefits from the ACIAR-managed contribution to the project (net present value, A$m)

	Adoption of zero tillage advanced by		
	3 years	5 years	8 years
Net gain to India (ACIAR-managed contribution)	238	453	739
ACIAR-managed contribution to project expenditure	1.3	1.3	1.3

Source: CIE calculations.

What if the benefits do not last for 30 years?

The cost–benefit analysis has assumed that the benefits from the adoption of zero tillage will continue undiminished for 30 years. Zero tillage has now been implemented for four years on some farms in Haryana and there is no evidence of any emerging problems. In fact, the benefits appear to be getting larger as the number of years it has been used increases.

Nevertheless, there is some probability that problems unforeseen now will arise with its continued use. This could include, for example, the emergence of another weed species as a significant problem. Table 11 attempts to account for this prospect by calculating benefits over a shorter payback period than 30 years. The table indicates that, even if the benefits are assumed to accrue for only ten years, the ACIAR project would still generate an extremely high ratio of benefits to costs. The ACIAR contribution, in terms of advancing the adoption of zero tillage by three years, does not change significantly.

Table 11. Comparing benefits for a range of payback periods (net present value, A$m)

	Benefits accrue for 30 years	Benefits accrue for 20 years	Benefits accrue for 10 years
Net gain to India	1809	1340	584
Net gain to India from ACIAR contribution	238	238	223

Source: CIE calculations.

Impact on poverty alleviation

About 36% of the Indian population live below the official poverty line (set by the Indian government). Punjab and Haryana are states with a relatively high average per capita income (around US$600 per capita for Punjab and US$550 per capita for Haryana) compared with the average for all India of US$400 per capita. But these averages conceal large numbers living in poverty.

The analysis in Table 8 showed that, once adoption of zero tillage reaches its maximum level, farmers in Haryana and Punjab will gain an extra $160 million/year in farm profits on wheat plantings covering 920,000 hectares—a gain of $174/ha/year. For a family cropping 5 hectares of wheat, this would amount to additional family income of $870/year, a significant increase over the state averages. The contribution of the project to poverty alleviation among poor farmers and farm workers in the region may well be substantial. Further work is needed to establish the project's direct and indirect contribution to poverty alleviation.

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References

Acharya, S.S. 2001. Domestic agricultural marketing policies, incentives and integration. In: Acharya, S.S. and Chaudhri, D.P., ed., Indian agricultural policy at the crossroads. Jaipur, India, Rawat Publications, 129–212.

Chand, R. and Jha, D. 2001. Trade liberalisation, agricultural prices and social welfare. In: Acharya, S.S. and Chaudhri, D.P., ed., Indian agricultural policy at the crossroads. Jaipur, India, Rawat Publications, 17–126.

Gill, G.S. 2002. Cross-resistance and multiple herbicide resistance in weeds and the need for innovative management strategies. In: Malik, R.K., Balyan, R.S., Yadav, A. and Pahwa, S.K., ed., Herbicide resistance management and zero tillage in rice–wheat cropping systems: proceedings of an international workshop, 4–6 March 2002. Hisar, India, Chaudhary Charan Singh Haryana Agricultural University, 1–5.

Malik, R.K. and Singh, S. 1995. Littleseed canary grass (*Phalaris minor*) resistance to isoproturon in India. Weed Technology, 9, 419–425.

Malik, R.K., Yadav, A., Singh, S., Malik, R.S., Balyan, R.S., Banga, R.S., Sardana, P.K., Jaipal, S., Hobbs, P.R., Gill, G., Singh, S., Gupta, R.K. and Bellinder, R. 2002. Herbicide resistance management and evolution of zero tillage—a success story. Hisar, India, Chaudhary Charan Singh Haryana Agricultural University, 43p.

Nagarajan, S., Singh, A., Singh, R. and Singh, S. 2002. Impact evaluation of zero-tillage in wheat through farmers' participatory mode. In: Malik, R.K., Balyan, R.S., Yadav, A. and Pahwa, S.K., ed., Herbicide resistance management and zero tillage in rice–wheat cropping systems: proceedings of an international workshop, 4–6 March 2002. Hisar, India, Chaudhary Charan Singh Haryana Agricultural University, 150–154.

Prabhu, L.P. and Heisey, P.W. 2001. Cereal-crop productivity in developing countries: past trends and future prospects. In: Alston, J., Pardey, P.G. and Taylor, M.J., ed., Agricultural science policy changing global agendas. Washington, D.C., International Food Policy Research Institute, 56–82.

Singh, R.P. and Kumar, P. 2002. Conservation tillage practice in rice–wheat system—an appraisal. In: Malik, R.K., Balyan, R.S., Yadav, A. and Pahwa, S.K., ed., Herbicide resistance management and zero tillage in rice–wheat cropping systems: proceedings of an international workshop, 4–6 March 2002. Hisar, India, Chaudhary Charan Singh Haryana Agricultural University, 103–104 and 136–140.

Singh, S.S., Prasad, L.K. and Upadhayay, A. 2002. Root behaviour, water saving and performance of wheat under zero tillage in heavy soils of south Bihar, India. In: Malik, R.K., Balyan, R.S., Yadav, A. and Pahwa, S.K., ed., Herbicide resistance management and zero tillage in rice–wheat cropping systems: proceedings of an international workshop, 4–6 March 2002. Hisar, India, Chaudhary Charan Singh Haryana Agricultural University, 103–104.

Sharma, R.K., Chhokar, R.S., Rani, V., Gathala, M.K. and Kumar, A. 2002a. Productivity, economics and energy requirement of rice–wheat system. In: Malik, R.K., Balyan, R.S., Yadav, A. and Pahwa, S.K., ed., Herbicide resistance management and zero tillage in rice–wheat cropping systems: proceedings of an international workshop, 4–6 March 2002. Hisar, India, Chaudhary Charan Singh Haryana Agricultural University, 127–130.

Sharma, R.K., Chhokar, R.S., Chauhan, D.S, Rani, V., Gathala, M.K. and Kumar, A. 2002b. Paradigm tillage shift in rice–wheat system for greater profitability. In: Malik, R.K., Balyan, R.S., Yadav, A. and Pahwa, S.K., ed., Herbicide resistance management and zero tillage in rice–wheat cropping systems: proceedings of an international workshop, 4–6 March 2002. Hisar, India, Chaudhary Charan Singh Haryana Agricultural University, 131–135.