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Impact of ICRISAT Research on Sorghum Midge on Australian Agriculture

International Crops Research Institute for the Semi-Arid Tropics

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Abstract

The most significant contribution from ICRISAT to Australian agriculture has been the introduction of improved sorghum midge (*Stenodiplosis sorghicola*) resistant lines combining desirable white grain and tan plant color through material such as ICSV 197, ICSV 745 and PM 13654. Overall, Australia has received significant benefits from ICRISAT's research on midge resistance in sorghum, at an average of A$1.14 million yr^{-1}.This is an example of international agricultural research output aimed at improving productivity in developing countries also having spillover benefits in developed countries. The spillover impacts in Australia from genetic materials developed and distributed through ICRISAT were analyzed in two levels. The first level is the identification of anticipated spillover benefits in terms of cost reduction for sorghum. The second level is the incorporation of price effects of international agricultural research for this crop. The price effects resulting from successful ICRISAT research were found to be significant. The lower prices for sorghum, as a result of increased production led to income reductions for Australian producers, and these were partly offset by the increased yields. The gains for the Australian consumers of these grains (ie, the Australian livestock sector) from the lower prices were significant, so that overall Australia made net gains from the impact of ICRISAT's sorghum research. These findings have important implications for international agricultural research, and recognition of these can assist in informed decision-making for research resources allocation and planning, and is likely to result in a more efficient and cooperative system worldwide.

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ICRISAT

International Crops Research Institute for the Semi-Arid Tropics

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Contents

Introduction

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has been developing germplasm and other technologies for the crops in its research mandate (sorghum, millets, chickpea, pigeonpea and groundnut) since 1972. Although ICRISAT aims to improve the production of these crops for developing countries, its germplasm and other technologies have been made freely available to developed countries. Australia has been regularly testing material from ICRISAT, and ICRISAT germplasm has been incorporated into a number of varieties released in Australia. However, prior to this study the utilization of ICRISAT research in Australia had not been documented.

A project was developed with the Australian Centre for International Agricultural Research (ACIAR), ICRISAT and New South Wales Agriculture to investigate and document the impact of ICRISAT research on Australian agriculture. The project "Spillover impact of ICRISAT research on breeding programs and agricultural production in Australia" was funded by ACIAR. The study aimed to:

1. Enable ICRISAT to understand better the role of its germplasm products in varietal development;
2. Identify the constraints and limitations of ICRISAT products and germplasm lines for Australian conditions and whether there has been any flow of Australian material back to ICRISAT;
3. Provide a basis for assessing whether other types of research outputs from ICRISAT are applicable to developed countries such as Australia; and
4. Identify any implications for Australia's investment in ICRISAT through foreign aid payments.

As in Brennan and Bantilan (1999), the main emphasis in this report is on the objectives 2, 3 and 4. The identification and assessment of those impacts on Australia will enable the first objective to be met by allowing ICRISAT to understand better the role of its different outputs in a developed country.

ICRISAT makes contributions in a wide range of areas, and will have made some critical contributions that are not captured in this report (Bantilan et al. 1997). In particular, ICRISAT has the unique role of collecting, evaluating and distributing germplasm to breeding programs worldwide. While the analysis in this report does not identify the value of those activities, ICRISAT plays a critical role as a source of diversity in Australian breeding programs. For example, the characterization of germplasm carried out at ICRISAT has produced critical evaluation information on germplasm, which is expected to improve the efficiency of breeding research.

ICRISAT's research on sorghum midge

ICRISAT's research on sorghum

There are several major target environments/cropping systems for sorghum improvement at ICRISAT:

1. Early maturity (Southern Africa)
2. Medium maturity (Global, India)
3. Late maturity (West and Central Africa)
4. Postrainy season crops
5. High-altitude, low-temperature environments (Eastern Africa)
6. Acid soil tolerance (Latin America)

ICRISAT's achievements to date have been mainly in the medium-maturity areas, which have 50% of world production of sorghum.

In the early to mid-1970s, the research was focused on breeding for all these regions at ICRISAT, Patancheru in India. By the early 1980s, it was evident that it was inappropriate to address the region-specific issues from one center in India. As a result, a number of other research centers were established in West Africa (Niger, Nigeria and Mali), Eastern Africa (Kenya), Southern Africa (Zimbabwe) and Latin America (Mexico).

In recent years, ICRISAT has withdrawn from its earlier emphasis on finished varieties, to the production of intermediate products, particularly: (a) parental lines for hybrids (male-sterile lines and restorer lines); and (b) lines with resistance to abiotic stresses, insect pests and diseases for use as parents in sorghum breeding programs. Since 1987, only trait-specific material has been distributed to the national agricultural research systems (NARS) and other cooperators worldwide.

Sorghum nurseries were initiated in 1972, with the foundation of ICRISAT. During the 1970s, the emphasis was on developing improved varieties, parental lines and hybrids with high grain yield and adaptability across the semi-arid tropics (SAT). Population breeding methods (reciprocal recurrent selection, halfsib, S_1 and S_2 testing) involving genetic male-steriles (ms_3 or ms_7) were extensively deployed to bring about necessary changes in traits associated with high and stable grain yields and plant architecture. A detailed analysis of sorghum in the semi-arid tropical environment during the later part of the 1970s led to identification of ten geographic functional regions, each having a set of yield constraints. Accordingly, importance was given to standardizing screening techniques to identify sources of resistance to various biotic and abiotic yield reducing constraints. Various projects targeted to improve high-yielding lines for resistance to various constraints through pedigree breeding methods were implemented in the 1980s. Pedigree breeding programs were implemented in breeding high-yielding varieties and parental lines for resistance to shoot fly, stem borer, midge, head bugs, grain mold, anthracnose, downy mildew, leaf blight, rust and *Striga* from 1976 through the 1990s. From 1990 onwards, pedigree breeding has been given increasing emphasis, and the recurrent population breeding methods have been de-emphasized, gradually reducing them to genepool improvement with mass selection towards the later part of the 1990s.

Trait-based pedigree breeding method was followed to develop male-sterile lines resistant to various stress factors in medium-maturity group. Simultaneous selection (for specific resistance trait based on families, and for high yield based on individual plants within the selected resistant families) and backcrossing to convert the maintainers into male-sterile lines were followed to develop trait-based male-sterile lines.

A conversion program enabled changing of several tall photoperiod sensitive *caudatum*, *guinea* and *kafir* sorghums into short, insensitive types during 1978–85. The research on grain quality, initiated in the late 1970s, was abandoned in the early 1980s as the variability was not significant. The research on grain food quality traits such as endosperm texture and hardness, milling ability, and malt and beer making qualities was taken up during the early 1980s at Patancheru and later on for Southern and Eastern Africa (SEA) in Bulawayo, Zimbabwe. This research was confined to mere monitoring the traits in the advanced lines in the late 1980s at ICRISAT, Patancheru. Similarly, malt and beer making qualities were monitored in the advanced lines in SEA after the 1980s.

The identification of geographic functional regions with a set of constraints accompanied by the pedigree breeding methods targeted to improve high-yielding varieties, parental lines and hybrids of varying maturities was the outcome of the gradual shift in breeding strategy from wide adaptability to specific adaptations, and to breeding threshold traits through the 1980s and 1990s. The wide-adaptability approach followed at ICRISAT, Patancheru was abandoned during the mid-1980s, and three research centers with regional mandates were established in Africa and one in Central America to take up breeding for region/production system-specific adaptations. These included early-maturity types for Southern Africa, medium-maturity varieties for India as well as for global targeting, late-maturity types with photoperiod sensitivity for Western and Central Africa. Research was also targeted to breed high-yielding sorghum by pedigree breeding for high altitude, low temperature environments of Eastern Africa during the 1980s and the early 1990s. Development of suitable cultivars with acid soil tolerance for Latin America was initiated through introduction of high-yielding lines from ICRISAT, followed by pedigree breeding.

There has been a gradual shift from developing finished products such as varieties and hybrids to developing intermediate products (trait-based genepools and trait-based parental lines) from 1990 onwards at ICRISAT, Patancheru. Furthermore, new breeding methods such as farmer participatory varietal selection (PVS), participatory varietal breeding (PVB), and marker and transgenic technologies have been used increasingly in recent years complementing breeding through the conventional pedigree breeding methods.

Sorghum midge research at ICRISAT

Distribution and biology of sorghum midge

A significant target of research at ICRISAT since the late 1970s has been host plant resistance to sorghum midge (*Stenodiplosis sorghicola*). From the 1970s, screening techniques were developed to identify sources of resistance (Sharma et al. 1992); since 1980, breeding for resistance was a major objective. Second-round derivatives such as ICSV 197 and ICSV 745 (midge resistance combined with white grain and tan plant type) were used extensively in the breeding programs during the late 1980s (Agrawal et al. 1987, Sharma et al. 1993, 1994). ICRISAT has developed standardized screening methods for midge resistance that are now generally used, and has studied the mechanisms, diversity and inheritance of resistance. It is difficult to value such an output but it will have significant influence on improved sorghum worldwide. ICRISAT has also developed high-yielding midge-resistant male-sterile lines. The information on pedigree and characterization of varieties/restorers and male-sterile lines is placed on ICRISAT's web-page.

Sorghum midge is distributed in Asia, Australia, Americas, Mediterranean Europe and Africa. Its northern limits include France, Italy, former USSR, Japan and USA; and the southern limits run through Argentina, South Africa and Australia. It is present in most of the countries within these limits, although its presence may not have been reported. It has spread as diapausing larvae in chaffy spikelets with sorghum seed to most of the countries where sorghum is grown.

Figure 1. Sorghum midge female ovipositing on a sorghum panicle (inset) and midge damaged panicle showing chaffy spikelets.

The adults are small, deep red in color, and have transparent brownish-black wings, 3 mm long (Fig. 1). The females have a long ovipositor. The adults emerge in the morning (0600 to 1100), and mate within an hour after emergence. The males emerge about half an hour earlier than the females, and hover around the spikelets where the females are about to emerge. A female lays 50 to 100 eggs, and peak oviposition occurs between 0800 and 1100. The females complete egg laying by mid-day, and most of them die before sunset. The eggs hatch in 2 to 3 days. The larvae feed on the developing grain for 10 to 15 days, and pupate inside the glumes. The adults emerge in 3 to 5 days. Life cycle is completed in 15 to 20 days, and there may be 10 to 15 generations in a year if the host plants are available continuously. As the sorghum midge larvae feed on the grains, these grains fail to develop and the damaged spikelets become chaffy. Midge damage is sometimes confused with poor seed setting due to unfavorable weather, genetic sterility and damage by head bugs and other insects.

Sorghum midge population builds up during the season, and the late flowering crops suffer heavy loss. Staggered sowings because of uneven rainfall at the beginning of the season, cultivation of sorghums with different maturities, and presence of alternate hosts increase sorghum midge damage. High temperatures during flowering may cause a decline in midge populations. Mean temperature of 25 to 30°C and relative humidity >60% are favorable for midge population buildup.

Extent of losses

Sorghum midge annually destroys about 10–15% of the sorghum crop. Sorghum planted early in a growing season usually escapes infestation, but the crop planted/flowering later in the season is severely damaged. Losses due to sorghum midge differ in intensity on a regional basis. Annual losses due to sorghum midge have been estimated to be US$292 million in the SAT, US$28 million in USA, and A$10 million in Australia. In India, annual grain yield loss due to sorghum midge and head bugs has been estimated to be US$100 million (Sharma and Teetes 1995).

Resistance screening techniques

Techniques to screen for resistance to sorghum midge have been described by Sharma et al. (1992). The major difficulties in identifying source material with stable resistance to sorghum midge have been due to: (a) variation in the flowering of sorghum cultivars in relation to midge incidence; (b) day-to-day variation in midge density; (c) competition with other insects such as head bugs; (d) parasitization and predation by natural enemies; and (e) sensitivity of midge to temperature and relative humidity. A large proportion of lines selected as less susceptible under natural conditions includes many early- and late-flowering genotypes that escape damage by the sorghum midge. Because of these problems, genotypes rated as resistant under natural infestation often turn out to be susceptible in the following seasons or at other locations. The following techniques have been standardized to screen for resistance to sorghum midge.

Field screening technique. Hot-spot locations are useful to screen for resistance to sorghum midge. Hot-spot locations for sorghum midge are Dharwad, Bhavanisagar and Pantnagar in India, and Sotuba in Mali. To screen test material for midge resistance under natural conditions, the periods of maximum midge density are determined through fortnightly sowing of a susceptible cultivar, and sowing dates are adjusted so that the most susceptible stage of the crop (flowering) coincides with greatest midge density. At ICRISAT, Patancheru, maximum midge density and damage have been observed in the crop planted during the 3rd week of July. The peak in midge density occurs during October. A second but smaller peak has been observed during March in the postrainy season, for which planting is carried out during mid-December. At Dharwad, the peak in midge abundance has been recorded during October, and the optimum time for sowing test material is between 20 July and 5 August. It is necessary to determine the appropriate time for sowing the test material to screen for resistance to sorghum midge effectively at different locations.

Midge abundance can be increased through infester rows and spreading sorghum panicles containing diapausing midge larvae in the infester rows (Sharma et al. 1992). Infester rows of cultivars CSH 1 and CSH 5 (1:1 mixture) are sown 20 days before the test material. Alternatively, early-flowering (40–45 days) lines (IS 802, IS 13249 and IS 24439) can be sown along with the test material. Four infester rows of a susceptible cultivar are sown after every 16 rows of the test material. Midge-infested chaffy panicles containing diapausing midge larvae are collected at the end of the cropping season. Chaffy panicles can be stored in gunny bags or in bins until the next season. Midge-infested sorghum panicles containing diapausing midge larvae are spread at the flag leaf stage of the infester rows. The panicles are moistened for 10–15 days to stimulate the termination of larval diapause. Adults emerging from diapausing larvae serve as a starter infestation in infester rows to supplement the natural population. Midge population multiplies for 1–2 generations on the infester rows before infesting the test material. A combination of infester rows and spreading sorghum panicles containing diapausing larvae increases midge damage 3–5 times. Infester rows alone also increase midge damage.

Sorghum head bug, *Calocoris angustatus* and midge parasite, *Tetrastichus diplosidis* are the two major insects limiting midge abundance in midge resistance screening trials. Mirid bugs damage the sorghum panicles from emergence to hard-dough stage and compete for food with sorghum midge. Also, adult mirid bugs prey on ovipositing midges at flowering. *Tetrastichus diplosidis* is an efficient parasite of sorghum midge at some locations. Less persistent and contact insecticides such as carbaryl and malathion are sprayed to control mirid bugs at the complete-anthesis to milk stage. The midge larvae feeding inside the glumes are not affected by the contact insecticides sprayed after flowering. Parasitism by *T. diplosidis* is also reduced in panicles sprayed at complete-anthesis to milk stage. The test material is sown twice at 15-day intervals to minimize the chances of escape from midge damage in early- and late-flowering lines; split sowing of the test material increases the efficiency of selection for midge resistance. Plant population affects the insect density per unit area, and in some cases influences the incidence and survival rate of insects. The level of midge damage has been observed to be higher at lower planting densities. Under field conditions, midge damage and efficiency of screening for midge resistance can be substantially increased by using a combination of timely sowing, spreading midge-damaged sorghum panicles containing diapausing larvae in the infester rows and split sowing, and selective use of contact insecticides for the control of mirid bugs and midge parasites. These techniques are useful in the initial large-scale screening of germplasm and breeding materials for resistance to sorghum midge.

Headcage technique. Caging midge flies with sorghum panicles is an important method for avoiding escape, and permits screening for midge resistance under uniform insect pressure. A headcage technique has been developed and standardized at ICRISAT, Patancheru. It consists of a cylindrical wire frame made of 1.5-mm diameter galvanized iron (GI) wire. The

Figure 2. Headcage technique to screen for resistance to sorghum midge: (a) sorghum panicle trimmed with scissors for infestation, (b) headcage placed around the sorghum panicle and covered with a cloth bag, and (c) aspirator used to collect midge adults.

loop attached to the top ring rests around the tip of the panicle, and the extensions of the vertical bars at the lower ring are tied around the peduncle with a piece of GI wire, or electric wiring clips. These prevent the cage from slipping when disturbed by wind or other external factors.

The step-wise procedure to screen sorghum for resistance to midge is as follows: Select sorghum panicles at 25–50% anthesis stage. Remove spikelets with dried-up anthers at the top, and immature ones at the bottom of the panicle with scissors so that only the spikelets at anthesis in the middle of the panicle are exposed to the midge flies for oviposition. Place the wire-framed cage around the sorghum panicle and cover it with a blue cloth bag (20 cm wide and 40 cm long) (Fig. 2).The cloth bag at the top has an extension (5 cm in diameter, 10 cm long) to release the midges inside the cage. Collect 20 adult female midges in a plastic bottle (a 200 ml aspirator) between 0800 and 1100 from flowering sorghum panicles (only female midges visit the flowering sorghum panicles and these are collected for use in infestation). Release 40 midges into each cage and close the inlet. Repeat the operation the next day. Infest 5–10 panicles in each genotype, depending upon the stage of material and the resources available. Examine the cages 5–7 days after infestation and remove any other insects such as mirid bugs, panicle-feeding caterpillars and predatory spiders. Remove the cages 15 days after infestation and evaluate the midge damage.

There may be some variation in midge damage over seasons because of temperature, rainfall and relative humidity, which influence both oviposition and damage by the sorghum midge. Midge damage decreases as the time of collection and release advances from 0830 to 1430. The headcage technique is quite simple, easy to operate and can be used on a fairly large scale to confirm the field resistance of selected genotypes. Changing weather conditions influence midge activity, and can affect midge damage under the headcage. In general, it is a thorough test for use in resistance screening, and is particularly applicable in identifying stable and durable resistance. For optimal stability, test material should be screened over several environments.

Identification of sources of resistance

Sources of resistance to sorghum midge have been identified by several workers. The genotypes IS 2579C, TAM 2566, AF 28, DJ 6514, IS 3461, IS 8918, IS 8891, IS 7005, IS 10712, IS 22881 and IS 27103 are stable and diverse sources of resistance to sorghum midge (Sharma et al. 1992, 1993, 2003).

Breeding for resistance

Figure 3. Midge-resistant sorghum ICSV 745 in farmer's field.

At ICRISAT, several lines with different maturity, plant height, panicle type and grain size have been developed (Sharma et al. 1992, 1993, 1994). Most of these lines were derived from DJ 6514 or its progeny ICSV 197 (DJ 6514 × IS 3443). Some breeding lines were also derived from crosses involving IS 12666C, IS 2579C, IS 18692, S-GIRL-MR 1 and IS 12573C. ICSV 197 is highly resistant to sorghum midge, and it yields 54% more than the resistant parent DJ 6514 (Agrawal et al. 1987). Using ICSV 197 as a resistance donor, several high-yielding lines with resistance to midge have been developed. Of these, ICSV 745 has been released in Karnataka in India, and has been widely tested on farmers' fields in Andhra Pradesh, Tamil Nadu and Maharashtra in India (Fig. 3); and Sudan. ICSV 735, ICSV 758 and ICSV 804 have been released in Myanmar. Cytoplasmic male-sterile (CMS) lines such as QL 38 and QL 39 have been developed in Australia (Henzell 1992). Male-sterile lines ICSA/B 88019 and ICSA/B 88020 have been developed at ICRISAT, Patancheru (Agrawal et al. 1996). These lines can be used to produce midge-resistant hybrids in combination with midge-resistant restorers.

Impact in Australia of ICRISAT's research on sorghum midge

Australian sorghum industry

Sorghum production in Australia has changed little over the past 20 years. It is a significant crop in Queensland (the leading producer) and New South Wales (Table 1). Only small areas of grain sorghum are grown in other states. On an average, in the ten years from 1987/88 to 1996/97, 551,000 ha were sown to sorghum each year, and the production averaged 1.2 million t.

Grain sorghum is grown mainly for the domestic livestock industries. Australia exported an average of 247,000 t of grain sorghum per year in the five years from 1992/93 to 1996/97, approximately 23% of production. Over that period, the gross value of production averaged A$188 million, while exports have been valued at A$51 million per year (ABARE 1997)[1]. Australian crop yields have averaged 2.12 t ha^{-1} over the ten years from 1987/88 to 1996/97.

The Australian sorghum industry is concentrated in Queensland, mainly in the Darling Downs, and in northern New South Wales. In these regions, sorghum midge has been a major constraint to production. Sowing time is important in handling sorghum midge. Crops sown in October–November can avoid midge, but later-sown crops that flower between mid-January and mid-March are likely to have a serious midge problem. The availability of midge-resistant genotypes has provided farmers with a window to adjust planting time according to rainfall pattern and crop rotations. Sorghum is also used as a forage crop, particularly for the dairy industry, in some regions.

Australian sorghum improvement program

The Australian sorghum improvement program is a mixture of public and private breeding efforts. The aim of the public sorghum breeding program is the development of germplasm (ie, breeding lines) for Australian conditions. Useful genetic material is made available and sold to the private sector on the basis of an up-front fee plus royalties if the material is used for producing varieties and hybrids. The development of hybrids for sale to farmers is carried out in the private sector. Approximately 80 lines were sold to the private sector breeders between 1989 and 1996. There are a number of private sector breeders aiming at developing hybrids for commercial use by farmers. Two of the major companies are Pioneer and Pacific Seeds.

1. All values in this report are in Australian dollars. In early 2001, one Australian dollar was worth approximately US$0.55.

Table 1. Area, production and yield of sorghum in states of Australia, 1987–96.					
Year	New South Wales	Victoria	Queensland	Western Australia	Australia
Area ('000 ha)					
1987/88	175	0	565	0	740
1988/89	152	1	468	1	622
1989/90	138	0	238	0	376
1990/91	84	0	291	1	376
1991/92	147	0	420	0	567
1992/93	118	0	308	0	426
1993/94	99	0	399	0	498
1994/95	161	6	519	0	686
1995/96	150	1	500	1	652
1996/97	126	1	435	2	564
Mean (10 yr)	135	1	414	1	551
Production ('000 t)					
1987/88	412	0	1213	0	1625
1988/89	301	1	934	1	1237
1989/90	359	1	578	1	939
1990/91	187	1	558	2	748
1991/92	398	0	1045	0	1444
1992/93	229	0	315	2	546
1993/94	228	0	852	2	1082
1994/95	347	8	916	2	1273
1995/96	450	2	1100	3	1555
1996/97	395	2	809	6	1212
Mean (10 yr)	330	2	832	2	1166
Yield (t ha^{-1})					
1987/88	2.35	-	2.15	-	2.19
1988/89	1.98	1.00	2.00	1.00	1.99
1989/90	2.60	-	2.43	-	2.49
1990/91	2.23	-	1.92	2.00	1.99
1991/92	2.71	-	2.49	-	2.54
1992/93	1.94	-	1.02	-	1.28
1993/94	2.30	-	2.14	-	2.17
1994/95	2.16	1.33	1.76	-	1.86
1995/96	3.00	2.00	2.20	3.00	2.38
1996/97	3.13	2.00	1.86	3.00	2.15
Mean (10 yr)	2.45	1.67	2.01	2.88	2.12

Source: ABARE, Australian Commodity Statistics 1997 (and previous issues); ABARE (1997).

The nationally-focused germplasm development program is managed by Dr RG Henzell of Queensland Department of Primary Industries (QDPI) and is based at the Hermitage Research Station, Warwick. The program involves a number of streams:

- Core breeding, germplasm development
- Pedigree analysis by molecular markers
- Nitrogen-use efficiency
- Physiology of the stay-green character
- Resistance to midge, aphids and *Helicoverpa*
- Coordination

A midge-tested rating scheme has been developed to enable the midge resistance of all lines to be assessed, and the information is provided to farmers. The general level of midge-resistance ratings has increased significantly from high susceptibility (8–9) to medium-to-high resistance (1–5), over the past 20 years. However, spraying for controlling the sorghum midge is still required for hybrids with the current level of midge resistance.

Use of ICRISAT's sorghum midge-resistant material in Australia

ICRISAT material of interest to Australia

In Australia, the main interest in ICRISAT sorghum material has been for the medium-maturity group. The ICRISAT-developed medium-maturity sorghum (65–70 days to flowering) types tend to delay in maturity under Australian conditions; hence, they cannot be adopted directly. However, the traits associated with these materials have been of value to Australia. The specific traits of use in Australia have been: (a) midge resistance; (b) white grain color; (c) tan plant color; and (d) stay-green trait.

Tan plant color is associated with leaf disease resistance as well as with reduced grain staining (pigmented glumes washed in rain result in discoloration of the grain). The stay-green trait confers stronger stalks, less terminal lodging and drought resistance. Australia has tended to use US (Texas) sources rather than ICRISAT sources for stay-green trait; so ICRISAT is not a primary source for this trait.

ICRISAT varieties such as ICSV 745 and PM 13654 and male-sterile lines such as ICSB 492 and ICSB 507 combine midge resistance with desirable white grain and tan plant color, and are being used extensively in Australia.

Efforts on midge resistance research started in QDPI in the 1970s. Progress towards incorporating midge resistance began in earnest in 1984, with research aiming to develop midge-resistant cultivars and to develop the understanding to enable farmer management practices to be effective. In late 1990s, about 80% of sorghum cultivars had some level of midge resistance, originally sourced from USA, although it is mainly low level resistance. On an average, midge attacks 50% of the Australian sorghum crop each year.

Australia has benefited from information on the sources identified from germplasm screening. The US sources of resistance were used in Australia's early breeding program; however, they were not in good agronomic background. While Australia has benefited from the information on resistant sources identified earlier, ICRISAT could not claim much of an impact from utilization of current midge-resistant sources in the breeding program.

Some of ICRISAT's earlier breeding derivatives (notably ICSV 197) were evaluated in Australia from 1984 onwards. The International Sorghum Midge Nursery has been sent to Australia for 10 years or so. Some of the early lines, mainly ICSV 745, have been used. The level of resistance that ICSV 745 can confer is equivalent to 5% increase in midge-affected crops (ie, 2.5% of all crops) (RG Henzell, QDPI, Australia, personal communication, 1996). Further, as ICSV 745 is different from other sources in use in Australia, it is expected to add to the genetic diversity in the breeding program. An addition to genetic diversity is also expected from the wild sorghums that have recently been collected in Australia; they are expected to add significantly to the genetic material in the germplasm collection, as they are believed to contain some important genes conferring resistance to sorghum midge.

ICRISAT's midge-resistant material in QDPI's sorghum breeding program

Of a total of 303 F_2 plants in the QDPI's sorghum breeding program in 1996, only six (2%) involved ICRISAT material, and each of those contained, by pedigree, 12.5% PM 13654. PM 13654 was chosen originally for its midge resistance (which was moderate), and also for its large white seeds and tan plant color.

Of the 6,993 F_3 plants in 1996, 992 (14%) involved ICRISAT material. About one-third of those involved ICSV 745 and ICSV 197, and they constituted 50% by pedigree of those F_3 lines. Remainder involved lines 31945-2-2 and 31925-2, each of which had 25% of PM 13654 in their pedigree. These two lines are involved in the six F_2 lines mentioned above. The line 31945-2-2 has a good level of stay-green and a moderate level of midge resistance and red grain with the 'I' gene, and is showing some grain weathering resistance. The line 31925-2 also has stay-green and midge resistance; it is white-grained and has tan plant color, although it has proved to be a poor restorer line.

Of the 500 F_4 lines in 1996, five (1%) involved ICRISAT material, being from the same cross as 31945-2-2. There were no lines with ICRISAT background in the F_5 and F_6 generations of the program in 1996.

In F_7 generation, there were two lines: 31945-2-2 and 31976, which have the same pedigree, but the latter is white-grained with tan plant color. By early 1996, only 31945-2-2 had been sold to the seed industry (as a hybrid restorer line). At that time, no hybrids based on it were being grown by farmers, although it was anticipated that the first use of that material by farmers could occur in 1997/98.

It was expected that the materials in F_3/F_4 stage will reach the final stage in 2002/03 and may find their way into farmers' fields. The reason for this delayed impact is that the midge-resistant lines developed at ICRISAT tend to be late under Australian conditions. Hence, the first cycle derivatives from such materials cannot compete readily with the advanced highly-adapted Australian materials. It is anticipated that the second-cycle materials derived from ICRISAT sources are those that would have perceptible impact on farmers' fields in the Australian environment. Attempts are therefore being made to combine the resistance from DJ 6514, using ICSV 197 and ICSV 745, with the midge-resistant lines produced in Australia. The two forms of resistance are reported to operate through different mechanisms.

During 1996, seed of the random mating 'Head Pest Population' and 50 pairs of midge-resistant male-sterile and maintainer lines has been imported into Australia from ICRISAT. This material can be used to extract lines with diverse mechanisms of resistance as well as incorporate resistance from maintainer lines into the Australian sorghum male-sterile lines. This will have a significant bearing on sorghum improvement, and midge resistance in particular, over the years to come.

Also, in a collaborative effort between ICRISAT and QDPI scientists, major insights have been gained in relation to diversity and mechanisms of resistance to midge, disposition and host selection behavior of midge, and evaluation of wild relatives of sorghum as alternative sources of resistance to this insect pest. The information gained will have a major impact on the selection of suitable midge-resistant parents, breeding strategies and the development of cultivars with stable resistance to sorghum midge.

Use of ICRISAT's sorghum midge-resistant material by private breeding programs

From 1987 onwards, Pioneer has been testing selections from ICRISAT, imported through Pioneer's Indian program (Bruce Boucher, Pacific Seeds, Australia, personal communication, 1996). A total of 400–600 lines have been imported, primarily for midge resistance. The process of introducing and evaluating these lines has been slow because of quarantine regulations. The material has now been screened, and the majority of the material has been shown to have much higher resistance than the existing Australian lines. These lines have also been found to have useful quality characteristics, including seed size and mold resistance. ICSV 197 has been the most successful. There are now 66 inbred pedigree lines in F_4 and F_5, with an average infusion of 13% of ICSV 197 in the restorer lines. Other progenies that are derived from ICRISAT material are in advanced stages in the program; their ICRISAT source materials include DJ 6514, PM 13957, PM 15952 and PM 15949. Pioneer has identified five lines (derived from midge-resistant lines introduced from ICRISAT in 1985) for use in their hybrid program:

1. ICS × PMX-214-84R-F_6 (ICSV 197 × R 12033)
2. ICS × PMX-215-84R-F_6 (ICSV 197 × R 12034)
3. ICS × PMX-248-85K-F_4 (PM 6751 × SPV 194)
4. ICS × PMX-255-85K-F_4 (PM 6751 × ICSV 102)
5. ICS × PMX-257-85K-F_4 (PM 6751 × ICSV 189)

In addition, Pioneer's sorghum program in 1996 had a number of ICRISAT lines being evaluated for midge resistance and dual-purpose or forage sorghum, both as restorer lines and female lines. The lines in the backcrossing stage have about 10% ICRISAT infusion, with a slightly higher level (13–15%) in the restorer lines.

Pioneer expects a release of a commercial hybrid from the ICRISAT materials in 2 to 4 years. The main characters sought in the Pioneer program are midge resistance and 'standability'. Pioneer releases an average of one hybrid each year (there were 5 in 1996). The aim is to have a replacement variety in advanced trials by the time a hybrid is three years old. The average life-span of a hybrid is approximately eight years. Pioneer plans to have 3 to 4 potential hybrids in farmers' trials each year, with one likely to be released. The aim for each variety is to have at least 5% yield gain, or multiple trait improvement. Yield has been increasing at around 1.0 to 1.5% per year (equivalent to 5% every 4 years).

Pacific Seeds also finds ICRISAT a useful source of germplasm, with similar emphasis on midge resistance. However, no grain sorghum varieties or hybrids have been released with ICRISAT materials in their pedigrees, and in 1996 there were no advanced grain sorghum lines containing ICRISAT materials. For forage sorghums, one late-maturing forage hybrid had one parent from ICRISAT, and several more were being developed by pedigree crossing, especially using late-maturity B-lines in single crosses. Pacific Seeds also uses the midge screening techniques developed at ICRISAT.

Impact of ICRISAT's midge-resistant material on Australian sorghum production

It is apparent that there had been no direct benefit by 1996 for the Australian sorghum industry from sorghum research at ICRISAT. However, there are a number of avenues by which ICRISAT material has been incorporated into advanced breeding materials now in use by breeding programs. The value of that material in commercial hybrids when grown in farmers' fields has yet to be established. However, it appears likely that hybrids with midge resistance and other useful characteristics from ICRISAT sorghum lines will be released for commercial use by farmers in the near future. When that occurs, it is likely that there will be a significant benefit for Australian sorghum producers, as the level of midge resistance conferred by the ICRISAT lines appears to provide a significant level of yield improvement.

One means of estimating the likely future impact is to assess the relative contribution of the yield improvement provided by ICRISAT's midge resistance research. An estimate of the impact at full adoption can be obtained on the basis of the following assumptions:

- Midge resistance from ICRISAT material (as in ICSV 197 and ICSV 745), in combination with other favorable plant traits such as tan plant color and white grain, would provide a 5% higher yield than the resistance that would be available otherwise.

- On average, midge attacks 50% of the Australian crop each year.

- Sorghum price is A$165 t^{-1} equivalent to total production cost per ton (GRDC 1992).

- Annual area sown to grain sorghum averages 551,000 ha, with average yield 2.12 t ha^{-1}.

On the basis of these assumptions, ICRISAT sorghum midge-resistant material would provide a cost reduction of A$4.02 t^{-1}, resulting in a benefit of A$4.7

million yr^{-1}, at full adoption (Table 2). This is a simplified analysis and provides only a partial measure of the full impact of ICRISAT sorghum research on the Australian sorghum industry. Other effects are likely to be felt through the impact on prices of ICRISAT's research. In the following section, a more complete analysis of the full impacts on Australia has been carried out.

The total benefits likely to be received depend on the adoption of the varieties with ICRISAT's midge-resistant lines, and the length of time that ICRISAT's contribution will provide benefits over those that would have been obtained without ICRISAT's contribution. The following adoption assumptions were made:

- Adoption begins in 1998/99.
- It takes 5 years for adoption to reach its peak, increasing linearly.
- Adoption stays at the peak level for a total of 20 years.
- Newer forms will replace the resistance after that time.

On the basis of these assumptions, the future gross benefits of the cost reduction due to ICRISAT midge-resistant lines available through ICSV 197, ICSV 745 and other lines are estimated as shown in Table 3. The discounted gross benefits, in 1996 values, are estimated to reach A$35.4 million over the twenty-five year period, averaging A$1.48 million yr^{-1}.

Economic analysis of impacts of ICRISAT's research on sorghum midge

Economic approach

The net benefits of agricultural research in a tradeable commodity for its target region are influenced by the spillover effects of that research to other producing regions with which the target region competes for a share of the world market. Edwards and Freebairn (1984) showed that the greater the extent to which the research innovations are adopted in other competing regions, the lower the net benefits for the target region. Davis et al. (1987) further developed the incorporation of spillover effects into the analytical framework for the evaluation of research.

In the analysis in this study, the spillover effects of research at ICRISAT on the production of sorghum in Australia have been identified. An attempt has also been made to quantify the extent of those spillover effects, largely through their effect on grain yields in Australia. A genetic improvement in yield results in

Table 2. Estimation of the value (A$ in 1996) of ICRISAT's research on midge resistance in sorghum for Australia.

Description	New South Wales	Queensland	Victoria	Western Australia	Australia
Sorghum base data[1]					
Area ('000 ha)	135	414	1	1	551
Production ('000 t)	330	832	2	2	1166
Yield (t ha^{-1})	2.45	2.01	1.67	2.88	2.12
Sorghum yield impact					
Yield increase from ICRISAT midge-resistant lines (%)	5	5	5	5	5
Proportion of area with midge (%)	50	50	50	50	50
Overall yield impact (%)	2.5	2.5	2.5	2.5	2.5
New yield (t ha^{-1})	2.51	2.06	1.71	2.95	2.17
Cost reduction in sorghum production					
Price/Total cost (A$ t^{-1})	165.00	165.00	165.00	165.00	165.00
Gross income/Total cost (A$ ha^{-1})	403.82	331.59	275.00	475.00	349.41
New cost (A$ t^{-1})	160.98	160.98	160.98	160.98	160.98
Cost reduction from improvement (A$'000)	4.02	4.02	4.02	4.02	4.02
Total value of ICRISAT contribution (A$'000)	1330	3348	6	8	4692

1. Average of ten years from 1987/88 to 1996/97.

Table 3. Estimated benefits for Australia from cost reduction in sorghum production.

Year	Gross benefits[1] (A$ million)				
	New South Wales	Queensland	Victoria	Western Australia	Australia
1997/98	0.00	0.00	0.00	0.00	0.00
1998/99	0.27	0.67	0.00	0.00	0.92
1999/2000	0.53	1.34	0.00	0.00	1.84
2000/01	0.80	2.01	0.00	0.00	2.76
2001/02	1.06	2.68	0.00	0.01	3.68
2002/03	1.33	3.35	0.01	0.01	4.68
2003/04	1.33	3.35	0.01	0.01	4.68
2004/05	1.33	3.35	0.01	0.01	4.68
2005/06	1.33	3.35	0.01	0.01	4.68
2006/07	1.33	3.35	0.01	0.01	4.68
2007/08	1.33	3.35	0.01	0.01	4.68
2008/09	1.33	3.35	0.01	0.01	4.68
2009/10	1.33	3.35	0.01	0.01	4.68
2010/11	1.33	3.35	0.01	0.01	4.68
2011/12	1.33	3.35	0.01	0.01	4.68
2012/13	1.33	3.35	0.01	0.01	4.68
2013/14	1.33	3.35	0.01	0.01	4.68
2014/15	1.33	3.35	0.01	0.01	4.68
Discounted total[2]	10.04	25.29	0.05	0.06	35.44
Discounted mean[2]	0.42	1.05	0.00	0.00	1.48

1. In constant 1996 Australian dollars.
2. Discounted to 1996 values at real discount rate of 8% per annum.

increase in productivity, which implies that there is higher output for each level of input. In economic terms, the yield-increasing effects of a new variety result in a shift of the supply curve (Lindner and Jarrett 1978, Norton and Davis 1981, Edwards and Freebairn 1984).

Following Edwards and Freebairn (1984), the increase in productivity is defined as a parallel vertical shift in the supply curve through a lowering of the production cost per ton. If the cost of growing the marginal hectare is E (A$ ha^{-1}) and the yield is Y (t ha^{-1}), the average cost of production is E/Y t^{-1}. If the yield increases by the proportion a with no increase in costs per hectare, then the cost per ton falls to $E/[Y(1+a)]$, and the proportional fall in costs is $a/(1+a)$ dollars per ton. Thus, a 'costless' (in terms perceived directly by the farmers) yield increase of 5.0% is equivalent to a cost reduction of 4.76%, or A$7.14 at an average total cost of A$150 t^{-1}.

It is assumed that the new varieties do not interact with changes in other inputs (see Brennan 1989, Brennan and Fox 1995), and the economic benefits can be estimated directly from these cost reductions.

The shifts in world supply attributed to research emanating from ICRISAT are likely to have had an impact on the world price for the relevant crops. It is likely, therefore, that the increased supply resulting from the increased productivity obtained through ICRISAT has affected the prices received for Australia's production of sorghum. The analysis in this study is based on estimates of supply and demand elasticities from ICRISAT studies. Since the markets are less than perfectly elastic, the increased supply in other countries will lead to reduced price, so that the gains indicated by this analysis are lower than if the assumption of perfect elasticity (as in Brennan and Fox 1995) had been maintained. As a result, these price effects are likely to have produced reductions in welfare for Australian producers of those crops, at the same time as producing benefits for Australian consumers.

Thus, the approach used in this study is a modified version of that used in the Brennan and Fox (1995) study of the impact of the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) on Australian wheat production. For the analysis of CIMMYT's wheat research in Australia, the supply shift was for a large export industry, for which the assumption of an elastic demand curve was reasonable. In addition, the nature of the impact was such that the development of the semi-dwarf wheats resulted in a large, one-off shift in the supply curve for wheat. However, for ICRISAT crops, all are smaller industries in Australia than wheat, and many are likely to have less elastic demand. Other features are that it is more difficult to identify the technological impacts, and that for some crops it is more a matter of potential impacts than actually realized impacts.

Spillover framework used

The framework used in this analysis is based on Edwards and Freebairn (1984). The world markets for each crop are disaggregated into two regions, namely Australia and Rest of World. Australia has been further sub-divided into states.

The following assumptions have been made for the analysis of the impact of spillovers in Australia:

- Elasticities of demand and supply are the same throughout Australia.
- All countries other than Australia are grouped into Rest of World.
- The total production cost per ton equal the equilibrium price (GRDC 1992).
- All supply and demand curves are linear.
- All shifts in supply are defined as vertical shifts (ie, cost reductions).

The framework used is illustrated in Figure 4. ICRISAT research leads to a shift in supply curves for each region. The shifts are greatest in the Rest of World (the 'target' region), with spillovers impacting on Australia. For simplicity in this analysis, the impact on developed countries other than Australia is ignored. The resultant welfare gains are measured as changes in producer and consumer surpluses for each region.

Empirical analysis of research impact

The genetic materials identified on the earlier analysis of the impact of ICRISAT research in Australia are expected to have their research impact starting in 1998/99, with their commercial impact on farms extending well past that time. In this analysis, an attempt has been made to quantify the impacts of the known research materials and their effect on hybrids and varieties released over the next five years.

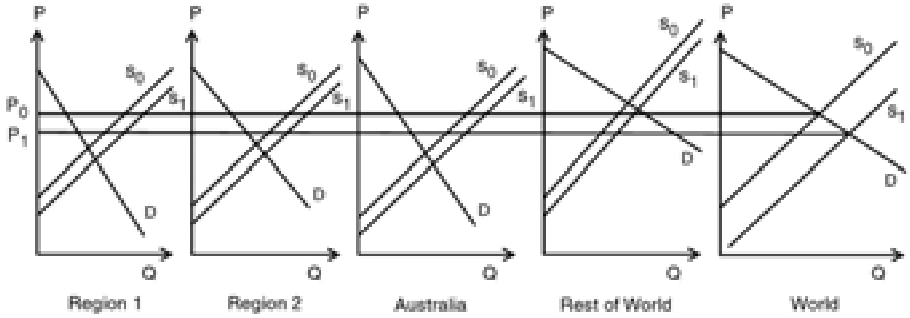

Figure 4. Framework for analyzing international agricultural research spillovers.

Table 4. Estimated ICRISAT impact on world sorghum production by 2002.

Research area	Area affected (million ha)	Expected yield increase (%)	Achievable by 2002 (%)
Grain, stover and forage yield breeding	45.02	1.0	1.0
Grain mold resistance and management	15.56	5.0	5.0
Anthracnose resistance	14.77	4.0	4.0
Foliar disease resistance	5.69	8.6	5.0
Head bug resistance and management	9.32	6.1	6.1
Midge resistance and management	15.95	10.0	7.0
Shoot fly resistance and management	6.90	5.0	5.0
Stem borer resistance and management	30.74	3.0	0.0
Low temperature resistance for highlands	0.80	1.0	1.0
Drought resistance breeding	7.66	5.3	0.0
Acid soil tolerance	0.81	8.0	8.0
Striga resistance and management	7.71	5.0	5.0
Gains from ICRISAT research	45.02	14.7	10.2

Source: ICRISAT (1992).

Beyond that time, there are likely to be further research impacts that are too difficult to estimate at this time. As a result, the impacts measured are those expected to occur through hybrids/varieties released over the next five years.

Estimates of the global impact of ICRISAT's sorghum research (Table 4) are that yields will increase by 14.7% as a result of current research. However, some of those gains are likely to be achieved well into the future, and it is estimated that the yields will increase by 10.2% over the next five years. Thus, the yield gains in the Rest of World will be 10.2% over that period, compared to 2.5% for Australia during the same period.

In assessing the impact of ICRISAT spillovers to Australia in sorghum research, the following data were used in the analysis:

- World sorghum price A$165 t^{-1}.
- Supply elasticity 0.3, demand elasticity -3.4 for Australia (Singh and Brennan 1998).
- Supply elasticity 0.2, demand elasticity -0.3 for Rest of World[2].

2. These elasticities are likely to vary considerably between countries.

- World sorghum production 58.358 million t.
- ICRISAT research will have increased sorghum yields by 10.2% in Rest of World by 2002, equivalent to a cost reduction of A$15.27 t^{-1}.
- Sorghum area in Australia 551,000 ha, production 1.2 million t and yield 2.12 t ha^{-1}.
- ICRISAT research will have increased Australian sorghum yields by 2.5%, equivalent to a cost reduction of A$4.02 t^{-1} by 2002.

The direct research impacts are a cost reduction of A$15.27 t^{-1} in Rest of World and spillover benefits of a cost reduction of A$4.02 t^{-1} in Australia. While these cost reductions result in savings for producers, because of increased production, the resultant increased quantities produced lead to a fall in price of A$5.52 t^{-1} or 3.35%. This leads to substantial benefits for consumers of these grains (ie, the livestock sector), while producers simultaneously face both yield increases and price falls. The net position of producers depends on the balance between the yield gains and the price fall.

Table 5. Annual welfare gains from ICRISAT's sorghum research at full adoption[1].

Description	Australia (A$ million)	Rest of World (A$ million)	World (A$ million)
Sorghum producers			
Price effect	-6.4	-312.6	-319.0
Yield effect	4.7	873.4	878.2
Net effect	-1.7	560.8	559.1
Sorghum consumers	5.3[2]	318.9	324.2
Total	3.6	879.7	883.3

1. Values are in 1996 Australian dollars.
2. Livestock sector.

Using these data the analytical framework provides the results shown in Table 5. For Rest of World producers, there is a large welfare gain of A$559 million yr^{-1}, with the yield increase more than offsetting the lower price. For Rest of World consumers, there are significant gains from the lower prices (A$324 million yr^{-1}). For Australia, the impacts are relatively smaller compared to the overall benefits from ICRISAT's research on sorghum. The cost reduction provides benefits of approximately A$4.7 million. However, the price reduction has a significant impact on the magnitude and distribution of those benefits. The net effects are a reduction in welfare for producers of A$1.7 million yr^{-1}, which results from a gain of A$4.7 million from the higher yields associated with ICRISAT's research on sorghum, but a reduction of A$6.4 million because of fall in world price by 3.4% from the same research on sorghum. Australian sorghum consumers (ie, the livestock sector) gain A$5.3 million from the lower prices, so that overall, there is a net gain to Australia of A$3.6 million.

These are the annual benefits that are expected at full adoption of the higher-yielding genotypes. On the basis that it would take five years for the research benefits to be fully adopted, with the first year of adoption being 1998/99, full benefits would not be achieved until 2002. The genotypes are assumed to have a productive life of a further 20 years beyond 2002 before being replaced or outmoded.

On the basis of these adoption parameters, the annual flow of benefits has been estimated over the period 1999 to 2022. When the annual benefits are discounted (at 8% per annum) over that period, there is an estimated net gain to Australia (in 1996 discounted dollars) of A$27.3 million, at an average of A$1.14 million yr^{-1}. Australian producers suffer a reduction in welfare averaging A$0.55 million yr^{-1} (despite an increase in yields), while Australian feed grain consumers gain an average of A$1.69 million yr^{-1} from the lower prices. In Rest of World, both producers and consumers reap substantial benefits from ICRISAT's research on sorghum midge, averaging A$177 million yr^{-1} and A$100 million yr^{-1} respectively, in discounted 1996 dollars.

To examine the extent to which the chosen values for the parameters of the analysis for sorghum have an impact on the findings of the study, the sensitivity of the results (measured as the aggregate gains for Australia) was examined (Table 6). Each selected parameter was varied by ±20%, and the effect on the gains for Australia estimated.

The aggregate results are clearly sensitive to the value of several parameters that have been used in the analysis. In addition, the relative gains of Australian sorghum producers and consumers vary with the values used. It is possible to identify 'break-even' points, the values at which Australian producers have net gains rather than net losses from ICRISAT's research on sorghum. These are:

- Yield gains in Rest of World are 7.2% or less.
- Yield gains in Australia are 3.5% or more.
- Elasticity of demand in Rest of World is larger (more negative) than -0.5.
- Elasticity of demand for Australia is larger (more negative) than -16.4.
- Elasticity of supply for Rest of World is less than 0.1.

Table 6. Sensitivity of results to changes in parameters[1].

Parameter	Value	Aggregate gain for Australia (A$ million)
Yield increase in Rest of World by 2002 (%)	10.20	1.14
	8.16	1.19
	12.24	1.10
Yield increase in Australia by 2002 (%)	2.5	1.14
	2.0	0.85
	3.0	1.42
Price (A$ t^{-1})	165	1.14
	132	0.91
	198	1.37
Elasticity of demand – Rest of World	-0.30	1.14
	-0.24	1.11
	-0.36	1.16
Elasticity of demand – Australia	-3.40	1.14
	-2.72	1.12
	-4.08	1.16
Elasticity of supply – Rest of World	0.20	1.14
	0.16	1.17
	0.24	1.11
Elasticity of supply – Australia	0.30	1.14
	0.24	1.14
	0.36	1.14
Years to peak adoption	5	1.14
	4	1.22
	6	1.06

1. Selected parameter values varied by +20% and -20% from values used in estimates.

The other parameters tend to shift the total benefits in unison, without changing the relativity between producers and consumers to any great extent.

Implications and conclusions

There are several implications of the findings of this study:

1. International centers such as ICRISAT remain a source of materials for potential yield gains for Australian crops, even if these are grown in systems and environments significantly different from those targeted by the international centers.

2. Australian producers will be affected by the price implications of the successful research that is undertaken by the international centers such as ICRISAT, whether or not they take advantage of the possible yield gains spilling over.

3. Consumers, which for many grains in developed countries means livestock industries, are likely to be significant benefactors of any research advances in the grain industries.

4. Australia's gains are likely to be greatest for those industries where there are significant links between Australian researchers and the researchers and programs being undertaken in the international research centers. As a result, personnel interchange and overseas visits by Australian researchers to those centers are likely to have enormous pay-offs for Australian grain industries, since they are a principal means of developing those links. The subsequent reduced time lag for the exchange of research information is also likely to result in increasing the impacts.

5. Australian researchers need to maintain their vigilance over international agricultural research developments. Only where Australian researchers can keep abreast of developments in other parts of the world can the benefits for Australian producers be maintained. Producers continually face the long-term decline in real prices that results from the ongoing success of the agricultural scientists around the world, in both national and international research, to increase yield levels for so many crops. The long-term decline in real prices will occur whether or not Australia contributes to the international agricultural research system, and Australia's best opportunity to glean spillover benefits from the system lies in being part of the system through financial support.

The decline in prices can lead to significant benefits for Australian consumers of grains, whether in consuming grain products directly or in consuming livestock products that use the lower-priced feed grains. In previous studies, those benefits to consumers in developed countries such as Australia have not been recognized, although they have been found in this study to be significant in some industries. The findings of this study mean that the importance of the price effects needs to be recognized in evaluating the economic benefits spilling over from international agricultural research. In conclusion, this study has produced significant findings at two levels. The first level has been the identification of anticipated spillover benefits in terms of cost reduction for producers of sorghum. Those cost reductions are expected to result from yield increases attributable to germplasm developed at ICRISAT or enhanced by being coordinated by ICRISAT and incorporated into genotypes that will be grown in Australia. The second level at which significant findings have emerged for the first time is in the incorporation of the price effects of international agricultural research for these crops. In this export-oriented Australian industry, the price effects were found to be significant, with a shift in welfare between the Australian producers of this grain and the Australian consumers and the livestock sector.

Recognition of these factors can lead to better-informed decision-making for research resource allocation and is likely to lead to a more efficient, and more cooperative, research system worldwide. The improved system will deliver expected improvements in the efficiency of production and in the delivery of appropriate food cheaply to the consumers in dire need.

Overall, Australia has received significant benefits from ICRISAT's research on midge resistance in sorghum, at an average of A$1.14 million yr^{-1}. Those benefits are well in excess of Australia's financial contribution to ICRISAT.

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Appendix 1. Survey of Australian research programs on contributions from ICRISAT

Survey of crop improvement programs

In late 1996, a survey was conducted of the crop improvement programs in Australia known to be working on ICRISAT's mandate crops. In all, twelve responses were received, with only one program known to be currently releasing varieties failing to supply a completed reply. A copy of the survey form is given below.

Survey of impact of ICRISAT on Australian agricultural production

1. Have you released varieties/hybrids that were developed by ICRISAT? If so, please provide details.
2. Have you released varieties/hybrids that have ICRISAT materials in their pedigree? If so, please provide details.
3. Are there ICRISAT materials in your advanced lines? If so, please identify the ICRISAT materials, and provide details of the stage of the lines.
4. Are you currently using ICRISAT breeding material in your crossing program? If so, please specify the main lines that you are currently using and the characteristics you are seeking from them.
5. Are there ICRISAT outputs other than breeding lines that you have used or are using (eg, screening techniques, nurseries, etc)? Please list.
6. Do you have regular contact with ICRISAT, such as regular visits? If so, please specify.
7. Any other comments on the impact of ICRISAT in Australia?

The aim of the survey was to discover the benefits that those involved in the research perceived for their programs from ICRISAT, and to identify the key materials involved and the strengths and weaknesses of that material. A further aim was to document which ICRISAT lines were currently being used by Australian breeders. The detailed results of the survey for sorghum are summarized.

Results of survey for sorghum

Release of varieties/hybrids developed by ICRISAT

No sorghum varieties or hybrids from ICRISAT had been released directly in Australia. The reason given was that cultivars developed by ICRISAT are not adapted to Australia, particularly with respect to later maturity and excessive height.

Release of varieties/hybrids with ICRISAT materials in their pedigree

Two sorghum lines (out of 94 released from the public breeding program since 1989) each have PM 13654 in their pedigree (12.5% by pedigree in each). One of these lines has white grain and tan plant color, derived from PM 13654. In addition, monsoon sorghum for northern Australia was reported as originating from material sourced from ICRISAT, although details of the actual materials used and crossings involved were not available.

Advanced lines with ICRISAT materials in their pedigree

The public breeding program reported that PM 13654-derived material is at an advanced stage (two have already been released). One breeding organization reported that there were no ICRISAT-derived materials in advanced lines for grain sorghum, but that for forage sorghum there were some late-maturity grain sorghums being used in pedigree crossing.

ICRISAT materials being used in current crossing program

The public sorghum breeding program is currently using PM 13654, ICSV 197 and ICSV 745. The latter two have been used to combine their (hopefully) different genes for midge resistance with those used in Australia. The stage of development varies from F_2 to F_4. Entomology and molecular marker research is being employed to test for differences in mechanisms and resistance genes. One breeding organization reported that there were no ICRISAT materials being used in their crossing program for grain sorghum, but for forage sorghum there were some late-maturity B-lines being used in single-cross steriles.

ICRISAT outputs other than breeding lines that are being used

For grain sorghum, midge screening techniques are being used.

Regular contact with ICRISAT

Sorghum researchers in Australia reported several visits to ICRISAT at Patancheru, India in recent years. In addition, there was regular written communication, particularly with Dr HC Sharma, who has been in Australia on sabbatical leave. Indigenous wild sorghum has been collected for, and sent to, ICRISAT.

Other comments on impact of ICRISAT in Australia

Breeders reported that ICRISAT is a very useful source of germplasm.

About ICRISAT

The semi-arid tropics (SAT) encompasses parts of 48 developing countries including most of India, parts of Southeast Asia, a swathe across sub-Saharan Africa, much of southern and eastern Africa, and parts of Latin America. Many of these countries are among the poorest in the world. Approximately one-sixth of the world's population lives in the SAT, which is typified by unpredictable weather, limited and erratic rainfall, and nutrient-poor soils.

ICRISAT's mandate crops are sorghum, pearl millet, chickpea, pigeonpea and groundnut – five crops vital to life for the ever-increasing populations of the SAT. ICRISAT's mission is to conduct research which can lead to enhanced sustainable production of these crops and to improved management of the limited natural resources of the SAT. ICRISAT communicates information on technologies as they are developed through workshops, networks, training, library services and publishing.

ICRISAT was established in 1972. It is supported by the Consultative Group on International Agricultural Research (CGIAR), an informal association of approximately 50 public and private sector donors; it is co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP) and the World Bank. ICRISAT is one of 16 nonprofit CGIAR-supported Future Harvest Centers.

ICRISAT

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