RESEARCH IMPACT EVALUATION

Cereal Rust Case Study

June 2016

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1 Executive Summary

The Challenge

Rusts are a common fungal disease of plants, including many of Australia's cereal and horticultural crops. They are a major disease of wheat and are prevalent in most wheat growing areas around the world, threatening global wheat yields.

Rust control relies on the use of fungicides and on breeding rust resistant wheat varieties that contain one or more genes conferring rust resistance. While control of cereal rusts based on breeding rust resistant varieties is the cheaper option for control, the need to use fungicides over the past years reflects the deficiency in breeding for resistance. This is because rust pathogens are adaptable and can evolve into new strains that can parasitise previously rust resistant plants. It is an ongoing battle to keep developing new wheat varieties that are resistant.

The Response

CSIRO has been contributing to the global fight against rust for several decades. CSIRO's research has focused upon the interaction between the rust pathogen and the crops it attacks. Through CSIRO's rust research, CSIRO has provided the wheat industry with genetic markers that simplify the conventional breeding of rust resistant wheat.

To date, CSIRO has provided wheat breeders with markers for more than 20 resistance genes, helping the industry keep one step ahead of this costly disease. These markers allow breeders to identify wheat varieties containing resistance genes which prevent rust infecting the plant or help the plants successfully battle a rust attack.

The Impact

CSIRO's cereal rust research has led to a range of impacts, including increased grain yield and reduced expenditure on fungicide application.

The net present value (NPV) of CSIRO's rust research for the wheat industry is approximately $382 million with $290 million attributable to CSIRO. The benefit-cost ratio (BCR) for the project and CSIRO is approximately 3.

This project provides an excellent example of how CSIRO has become an important and trusted adviser to the Australian grain industry and enabled the industry to address a range of scientific and technical challenges and help it to grow its business over time.

This case study uses the evaluation framework outlined in the CSIRO Impact Evaluation Guide. The results of applying that framework to the Cereal Rust case study are summarised in Figure 1.

INPUTS	ACTIVITIES	OUTPUTS	OUTCOMES	IMPACT
• CSIRO investment (FTE, in-kind contributions, equipment/facilities and background IP) • Funding from GRDC, 2Blades Foundation, ACIAR, and Gates Foundation • Costs of adaptive development and local extension by farmers	• Development of molecular markers for wheat rust resistance genes • Marker validation on wheat germplasm collections	• 21 molecular markers released to wheat breeders in Australia and overseas • Germplasm containing marker tagged resistance genes • Publications • Rewards	***Uptake and Adoption*** • Adoption of molecular markers by both Australian and international wheat breeding community • Improved breeding of rust resistant wheat varieties • Rust resistant wheat cultivars used extensively by growers	***Economic impact*** • Increased grain yield • Reduced expenditure on fungicide application ***Environmental impact*** • Reduced contamination of waterways through avoided fungicide use. ***Social impact*** • Increased resilience of regional communities • Contribution to food security

Figure 1: Impact Pathway for Cereal Rust Project

2 Purpose and audience

This evaluation is being undertaken to demonstrate (to a range of stakeholders) the positive impacts arising from CSIRO's Cereal Rust research. This case study can be read as a standalone report or aggregated with other case studies to substantiate the impact and value of CSIRO's activities relative to the funds invested in these activities.

This case study is proposed for accountability, reporting, communication and continual improvement purposes. Audiences for this report may include members of Parliament, Commonwealth Departments, CSIRO and the general public.

3 Background

Since the first European settlement of Australia, production of cereal grain for local consumption and export has been threatened by fungal rust diseases. Rusts are a common fungal disease of plants, including many of Australia's cereal and horticultural crops. There are three species of wheat rust - leaf, stripe and stem. These are considered major diseases of wheat and are prevalent in most wheat growing areas around the world, threatening global wheat yields and, in the case of stem rust, can destroy entire wheat crops. For example, Beddow et al 2015 estimated that globally

5.47 million tonnes of wheat are lost to the stripe rust pathogen each year, equivalent to a loss of US$979 million per year.

Rust control relies on the use of fungicides and on breeding rust resistant wheat varieties that contain one or more genes conferring rust resistance. While control of cereal rusts based on breeding rust resistant varieties is the cheaper option for control, the need to use fungicides over the past years reflects the deficiency in breeding for resistance. This is because rust pathogens are adaptable and can evolve into new strains that can parasitise previously rust-resistant plants. It is an ongoing battle to keep developing new wheat varieties that are resistant.

In a research program beginning in 1982, CSIRO has made major contributions to our understanding of the interactions of plants and pathogens. CSIRO's research has focused upon the interaction between rust pathogens and the crops they attack. Using CSIRO's expertise in wheat genetics CSIRO investigates both plants' defence mechanisms and rusts' ability to infect host plants.

The Program's rust resistance research is undertaken as part of the national Australian Cereal Rust Control Program funded by the Grains Research and Development Corporation (GRDC) and including collaborating partners from CSIRO, the Universities of Sydney and Adelaide, and the International Maize and Wheat Improvement Center (CIMMYT), Mexico.

4 Impact Pathway

Project Inputs

Cereal rust research has been the recipient of investment from a range of research and development organisations. CSIRO carries out a number of projects in wheat rust research through funding partnerships with the Grains Research and Development Corporation (GDRC), 2Blades Foundation, Australian Centre for International Agricultural Research (ACIAR) and the Bill & Melinda Gates Foundation. Estimates of the funding by institution for the project are shown in Table 1.

Table 1: Total investment in the Program between 1995 and 2015 (real $)

Year	CSIRO $ m)	CIMMYT ($ m)	University of Sydney ($ m)
1995	3.4	0.2	0.2
1996	3.4	0.2	0.2
1997	3.4	0.2	0.2
1998	3.4	0.2	0.2
1999	3.4	0.2	0.2
2000	3.4	0.2	0.2
2001	3.4	0.2	0.2
2002	3.4	0.2	0.2
2003	3.4	0.2	0.2
2004	3.4	0.2	0.2
2005	3.4	0.2	0.2

2006	3.4	0.2	0.2
2007	3.4	0.2	0.2
2008	3.4	0.2	0.2
2009	3.4	0.2	0.2
2010	3.4	0.2	0.2
2011	3.4	0.2	0.2
2012	3.4	0.2	0.2
2013	3.4	0.2	0.2
2014	3.4	0.2	0.2
2015	3.4	0.2	0.2
Total	**70.4**	**4.2**	**4.2**

Note: a) all dollars are real in 2015 dollars, b) Total investment is based on 5- year average between 2012 and 2016 and c) Partner contribution is based on 50:50 split.

Activities

CSIRO Plant Industry has been involved in rust research since the early to mid-1980s. CSIRO's work aims to simplify breeding for resistance and develop durable and effective genetic control of wheat rusts through conventional and Genetically Modified (GM) breeding.

Early research focused on understanding the molecular interactions between plants and pathogens in model plants (flax and maize). In recent years, research has been directed towards cloning wheat rust resistance genes and wheat rust avirulence genes. The application of bioinformatics has also radically changed experimental designs for wheat rust research at CSIRO.

In the long term, CSIRO aims to develop wheat varieties with long-lasting rust resistance by cloning and packaging several resistance genes into a single transferrable genetic unit. Such a gene unit would stay permanently together so breeders would only have to keep track of one large resistance gene stack rather than many single genes spread over different chromosomes. This would also limit the potential of the rust pathogen to overcome a single rust-resistance gene through evolution.

Outputs

CSIRO's rust research has provided the wheat industry with genetic markers that simplify the conventional breeding of rust resistant wheat. These markers help breeders to identify wheat varieties containing resistance genes which either prevent rust infecting the plant or enable plants to successfully battle a rust attack.

To date, CSIRO has developed 21 molecular markers that have been distributed to breeders in Australia through the GDRC. The molecular markers have also been released overseas through CIMMYT which distributes around 70% of the world supply of wheat germplasm.

Table 2: A list of marker information and reference

Lr37/Sr38/Yr17	NBS-LRR derived, dominant marker from alien segment. Cosegregates with triple rust resistance gene.	Seah et al 2001, Theoretical and Applied Genetics 102:600-605
Lr34/Yr18/Pm38/Sr57	Gene specific (perfect marker) for adult plant resistance gene to leaf rust, stem rust and stripe rust.	Lagudah et al 2009, Theoretical and Applied Genetics 119:889-898
Lr46/Yr29/Sr58/Pm39	Marker tightly linked to gene for adult plant resistance to leaf rust, stem rust and stripe rust.	Dr Evans Lagudah
Sr46	Perfect marker for resistance to stem rust.	Dr Evans Lagudah
Sr2	EST derived, very tightly linked, dominant marker for resistance to stem rust.	Dr Rohit Mago and Mr Wolfgang Spielmeyer
Sr50 (SrR)	AFLP derived, tightly linked, dominant marker. Amplifies from shortened 1RS chromosome (not sticky) for resistance to stem rust.	Mago et al 2002, Theoretical and Applied Genetics 104:1317-1324
Sr31	RFLP derived, tightly linked, co-dominant marker. Amplifies from shortened 1RS chromosome (not sticky) for resistance to stem rust.	Mago et al 2002, Theoretical and Applied Genetics 104:1317-1324
Sr24/Lr24	AFLP derived, tightly linked, dominant marker for resistance to stem rust.	Mago et al 2005, Theoretical and Applied Genetics 111:496-504
Sr26	AFLP derived, tightly linked, dominant marker for resistance to stem rust.	Mago et al 2005, Theoretical and Applied Genetics 111:496-504
Sr39	AFLP derived, tightly linked markers. Separate markers for R and S. Can be combined for co-dominant marker for resistance to stem rust.	Mago et al 2009, Theoretical and Applied Genetics 119 (8): 1441-1450
Sr22	Perfect marker for resistance to stem rust.	Periyannan et al 2011 Theoretical and Applied Genetics, 122:1-7; Dr Sam Periyannan, Dr Evans Lagudah
Sr32	AFLP derived, tightly linked marker for resistance to stem rust.	Mago et al 2013, Theoretical and Applied Genetics 10.1007/s00122-013-2184-8
SrAes1t	AFLP derived, tightly linked marker for resistance to stem rust.	Mago et al 2013, Theoretical and Applied Genetics 10.1007/s00122-013-2184-8
SrB	Tightly linked marker for resistance to stem rust.	Rohit Mago, Unpublished

Sr33	Perfect marker for resistance to stem rust.	Periyannan et al 2013, Science 341:786-788
Sr45	Perfect marker for resistance to stem rust	Periyannan et al 2014 Theoretical and Applied Genetics 127:947-955; Dr Sam Periyannan, Dr Evans Lagudah
Lr67/Yr46/Sr55/Pm 46	Perfect marker for adult plant resistance gene to leaf rust, stem rust and stripe rust.	Moore et al 2015, Nature Genetics DOI 10.1038/ng.3439

Source: CSIRO

Publications

CSIRO has produced high profile papers on rust research which have appeared in journals such as *Nature Genetics* and on the cover of *Science.*

Steuernagel B, Periyannan SK, Hernández-Pinzón I, Witek K, Rouse MN, Yu G, Hatta A, Ayliffe M, Bariana H, Jones JDG, Lagudah ES, Wulff BBH (2016) MutRenSeq; three-step cloning of resistance genes from hexaploid wheat using mutagenesis and sequence capture. Nature Biotechnology: (in press)

Mago R, Zhang P, Vautrin S, Šimková H, Bansal U, Luo M-C, Rouse M, Karaoglu H, Periyannan S, Kolmer K, Jin Y, Ayliffe M, Bariana H, Park RF, McIntosh R, Doležel J, Bergès H, Lagudah E, Ellis JG, Dodds PN. The wheat *Sr50* gene reveals rich diversity at a cereal disease resistance locus. Nature Plant 1, 15186.

Moore JW, Herrera-Foessel S, Lan C, Schnippenkoetter W, Ayliffe M, Huerta-Espino J, Lillemo M, Viccars L, Milne R, Periyannan S, Kong X, Spielmeyer W, Talbot M, Bariana H, Patrick JW, Dodds P, Singh R, Lagudah E (2015) Recent evolution of a hexose transporter variant confers resistance to multiple pathogens in wheat. Nature Genetics 47, 1494-1498.

Periyannan S, Moore J, Ayliffe M, Bansal U, Wang X, Huang L, Deal K, Luo M, Kong X, Bariana H, Mago R, McIntosh R, Dodds P, Dvorak J, Lagudah E. (2013) The Ug99 effective wheat stem rust resistance gene *Sr33* is an ortholog of barley *Mla* genes. *Science* 341, 786 – 788

Dodds P.N., Lawrence G.J., Catanzariti A-M., Teh T., Wang C-L, Ayliffe M.A., Kobe B., Ellis J.G. (2006) Direct protein interaction underlies gene-for-gene specificity and coevolution of the flax L5/L6/L7 resistance genes and flax rust avrL567 avirulence genes. *Proceedings of the National Academy of Science USA* 103, 8888-8893.

Catanzariti A-M., Dodds P.N., Lawrence G.J., Ayliffe M.A., Elllis J.G. (2006) Haustorially-expressed secreted proteins from flax rust are highly enriched for avirulence elicitors. *Plant Cell* 18, 243-256.

Dodds, P.N., Lawrence, G.J., Catanzariti, A-M., Ayliffe, M. and Ellis, J.G. (2004) The Melampsora lini AvrL567 avirulence genes are expressed in haustoria and their products are recognised inside plant cells. *Plant Cell* 16, 755-768.

Awards

In 2013, CSIRO (as a member of the Australian Cereal Rust Control Program which is supported by the GDRC) was awarded the Borlaug Global Rust Initiative’s Gene Stewardship Award for efforts to combat wheat rust diseases.

CSIRO's rust research team also won the CSIRO medal in 2004.

Two team members have been elected to the Australian Academy of Science and one member has been elected to the Royal Society.

Outcomes

Adoption

Breeding companies in Australia via the GDRC have adopted CSIRO molecular markers into their breeding programs. Further, the published work of CSIRO has allowed international adoption of these DNA markers into all breeding programs. There are at present around 100 wheat cultivars grown in Australia, 60% of which have resistance genes that are tagged by CSIRO-developed markers.

Table 3: Outcomes of selected adopters

Beneficiary	Outcome
CIMMYT- CGIAR centre for wheat improvement	CIMMYT has adopted markers developed at CSIRO and in the last 5 years have routinely used markers for Sr22, Sr25, Sr26, Sr45, Sr50, Sr55/Lr67, Lr34, Lr46 and Sr2 rust resistance genes.
Private and public wheat breeding in Australia (eg LongReach, AGT, EGA etc)	A suite of over 20 rust resistance gene markers has been provided to Australian breeding companies to use in their breeding programs.

Source: CSIRO Plant Industry Science Review 2006.

The program's development of industry-relevant and applicable rust resistance gene markers are being taken up by breeders in Australia and internationally. These markers offer simple, accurate and broadly useful means of identifying, selecting and pyramiding rust resistance genes in the widest possible range of breeders' germplasm. The marker technology has greatly enhanced wheat rust resistance breeding because of its ease and accuracy in pyramiding resistance genes.

Impacts

CSIRO rust research has led to a range of delivered and potential impacts, including increased yield and grain quality, reduced adverse environmental impacts and protection of employment. Using CSIRO's triple bottom line impact classification approach, Table 4 summaries the nature of the existing and potential impacts.

Table 4: Impact of Cereal Rust Research

TYPE	CATEGORY	INDICATOR	DESCRIPTION
Economic	Productivity and efficiency	Increased grain yield	Overall reduction in crop loss due to the rust resistance of the varieties using CSIRO molecular markers, meaning higher yields for Australian grain growers.

Economic	Productivity and efficiency	Reduced costs of fungicides and their application	Reduced costs to growers through avoided fungicide applications to resistant varieties.
Environmental	Aquatic environments	Water quality	Reduced fungicide application resulting in potentially fewer contaminants exported to waterways.
Social	Resilience	Income and employment	Improved capacity of growers to prevent rust epidemics potentially contributes to greater stability in production and employment in rural communities.
Social	Security	Crop yield	At a national level, rust resistance has potentially contributed to a higher level of food security.

Of the benefits identified, economic benefits are estimated in monetary terms, as discussed in the section below. Given the constraints to data availability for environmental and social benefits, these benefits are noted, but not assessed.

5 Clarifying the Impacts

Counterfactual

Although there are other organisations in Australia and overseas that could have developed molecular markers and have them adopted by industry, CSIRO was successful in doing this because of its world leading expertise, sizeable team, national and international collaborations, close interactions with pathologists and long term commitment to rust resistance research.

In addition, it is important to note the following:

- It is not profitable for commercial companies to produce markers for rust resistance. Firstly, rust pathogens are continuously evolving, making it costly and time consuming to continuously create new markers and identify new sources of resistance. Secondly, a significant, ongoing investment in specialists in rust pathology and molecular biology is needed; breeders do not have the facilities, time, expertise or resources to develop molecular markers for rust diseases.
- Rust diseases are a global threat that can only be countered by the development of rust resistant cultivars in all wheat growing regions. Consequently CSIRO rust resistance gene markers have been freely distributed to promote international adoption of resistant cultivars. Commercial entities are unlikely to undertake this public good research.
- CSIRO has been involved in rust resistance research for more than 30 years, giving it an advantage in terms of experience, and connections to pathologists and industry for rapid deployment of markers. Its national and international collaborations ensure it has the most current information regarding new rust outbreaks and current resistance gene deployment strategies.

If CSIRO's involvement and investment in the Cereal Rust program had not been made, it is assumed that there would not have been significant molecular marker research by the private sector or state governments. It is also assumed that without CSIRO's involvement and investment in the Cereal Rust program, there would have been few new molecular markers for rust disease resistance produced and conventional varieties produced by cereal breeders would probably contain few rust disease resistance genes.

Attribution

CSIRO was the primary source of research, wheat genetics and resources that underpinned the understanding of the interaction between the rust pathogen and the crops it attacks, which provided the wheat industry with the means to breed rust resistant wheat. Other collaborators to the successful implementation of CSIRO research include GRDC, CIMMYT and University of Sydney, which either provided important co-financing or contributed to the marker development such as scoring lines.

Since all of the CSIRO, CIMMYT and University of Sydney research were considered necessary to achieve the ultimate objective of providing the wheat industry with genetic markers that simplify the conventional breeding of rust resistant wheat, it was appropriate to attribute benefits among the project on a cost-sharing basis. CSIRO accounted for approximately 80 per cent of the total research costs. Consequently, in this analysis, it is assumed that roughly 80 per cent of research impacts arising from the new genetic markers can be attributed to CSIRO.

6 Evaluating the Impacts

Cost Benefit Analysis

Definition

This section provides definition of key input costs, benefits and our method of calculating the benefit cost ratio (BCR) in this analysis.

Input costs are the costs incurred by CSIRO and its research partners to produce the research outputs and include cost associated with such things as staff, in-kind contributions, equipment/facilities and background IP. Where data is available, input costs should also include usage and adoptions costs borne by the end users such as costs of any trials, further development and market tests.

Benefits represent the avoided economic loss from stem rust for Australian grain growers, which is calculated by relating the per-hectare costs to the number of hectares of the crop sown. In this analysis, we used industry value added measurement (also called 'industry gross product') to monetise the benefits , which is derived by subtracting production value with costs of goods and services using a 10 year average proportion of value added in the wheat industry.

Therefore, the formula for calculating a benefit cost ratio is defined as industry value added benefits (Present Value) divided by all the research, adaptive development and extension costs

(Present Value). This ratio can also be interpreted as a "Profitability Ratio" or "Net Benefit/Investment Ratio".

Time period of analysis

Where CSIRO research programs such as the rust resistance program is an ongoing activity, it is necessary to define a particular period for the economic analysis. CSIRO Plant Industry has been involved in rust research since the early to mid-1980s, and so defining a period for this analysis is difficult. However, given the available data, the analysis is based on research activity since the mid-1990s.

In rust resistance research, there are lags between the genes being identified and the release of a molecular marker for adoption by wheat breeders. In wheat breeding, there are also lags between the cross being made and the release of an improved variety. In recent years, these lags have averaged approximately 10 years, so that adoption on farms does not take place until the eleventh year after the initial cross. On that basis, the benefits are only measured from 2006 onwards. In the analysis, the costs from 1995 to 2015 are included.

Given the costs are measured until 2015, the benefit must be estimated for the future, since CSIRO's research developed before 2015 will have a productive impact for many years. Brennan and Bialowas (2001) found that varieties are grown for approximately 17 years after release. In this analysis, we take a conservative approach and measure the benefits to 2025. Thus the analysis involves a large component of ex-post analysis (relating to the period 1995 -2015), but also involves some ex-ante analysis for the benefits flowing from those activities over the period to 2025.

Defining the "with" and "without" scenarios

Murray and Brennan (2009) argued that value of the current control measures such as breeding rust resistance to disease can be shown by the difference between the outcome if there were no controls and the outcome with controls in place.

$C = G_p - G_c$

Where G_c and G_p are, respectively, the current and potential aggregate losses ($) of the diseases across a production zone; and C is the aggregate value ($) of current control measures. Murray and Brennan (2009) collected information from 14 production zones where wheat is grown in Australia with similar soils and climate. These production zones included:

Northern Region

1 Queensland Central Q Cen

2 NSW North-East/Queensland South-East NNEQSE

3 NSW North-West/Queensland South-West NNWQSW

Southern Region

4 NSW Central N Cen

5 NSW–Victoria Slopes NV Slp

6 Victoria High Rainfall Vic HR

7 Tasmania Tas

8 SA–Victoria Border–Wimmera SV BWim

9 SA–Victoria Mallee SV Mall

10 SA Mid-North/Lower Yorke, Eyre SMNLYE

Western Region

11 WA Sandplain–Mallee W SandM

12 WA Central WA Cen

13 WA Northern WA N

14 WA Eastern

Table 5: Value of Disease Control for Rust in Wheat ($m, 2009 terms)

Disease	Stem Rust	Stripe Rust
Costs ($m)		
Potential cost	478	994
Present cost	8	127
Value of control	470	868
Contribution (%) from		
Breeding	93	50
Cultural/Rotational	5	9
Pesticides	2	41
Contribution ($m) from		
Breeding	438	431
Cultural/Rotational	24	78
Pesticides	8	359

Source: Murray and Brennan 2009

We believe that the best way to define the “with” and “without” scenarios is to adopt the approach employed by Murray and Brennan (2009) as this is the key benefit CSIRO delivers. In effect CSIRO’s cereal rust research provides protection for the industry against serious disease outbreaks and economic risks. In this analysis, we assume that the difference between the potential costs and the actual costs with control is the value of disease controls. Due to data constraints, this analysis focuses on just one rust disease, stem rust, which can destroy entire wheat crops.

In this analysis, the value of diseases control figures that form the basis of Murray and Brennan 2009 estimates are assumed to be constant for the full duration of the project life to 2025. It is likely that the number of incidences and level of severity will be different each year, which results in variable economic values of disease controls. Given the data constraints, no attempt was made to change the estimates for each year to 2025.

The focus of CSIRO’s molecular marker research is on understanding and furthering knowledge associated with rust resistance in cereals to improve germplasm and screening services. This research is usually considered as a pre-breeding program rather than a breeding program per se. There were other activities required before rust resistant varieties could be produced by cereal breeders, most notably the development of rust resistant germplasm. In most cases the germplasm containing the resistance gene is essential for marker development. On that basis, we conservatively assume here that CSIRO’s research contributes 20 per cent of the improvement in a breeding program. We therefore assume in the base case scenario that 20 per cent of the research impacts can be attributed to CSIRO, although this is allowed to vary between 15 per cent and 25 per cent in the sensitivity analysis.

Table 6: Value of Disease Control for Stripe Rust in Wheat ($m per annum, 2015 terms)

	Economic costs
- With program (A)	9
- Without program (B)	549
- Difference (C= B-A)	540
Attribution due to Breeding (D)	93%
Attribution to CSIRO markers(E)	20%
Proportion of value added (F)	26%[a]
Economic costs avoided (G=C*D*E*F)	26.4

Note: a) 10 year average of the wheat industry (IBIS World)

Source: Based on Murray and Brennan 2009 (CPI adjusted)

Costs

Establishing the costs involved throughout the entire inputs to impact pathway is an important exercise of a cost-benefit analysis. This includes both the input costs incurred by CSIRO and its researcher partners, as well as any usage and adoption costs borne by clients, external stakeholders, intermediaries and end users. Given the length of the project and commercial confidentiality issues, we were unable to identify usage and adoption costs borne by intermediaries and end users of CSIRO markers. For the purpose of this evaluation, we only included research costs incurred by CSIRO, CIMMYT and University of Sydney.

As noted in previous sections, CSIRO, CIMMYT and University of Sydney contributed $3.35 million, $0.2 million and $0.2 million per annum to the project between 1995 and 2015 in real terms. These contributions were discounted using a real discount rate of 7%. Table 7 summarises the adjusted research costs for CSIRO, CIMMYT and University of Sydney.

Table 7 Summary of Cereal Rust adjusted program costs

Year	CSIRO $ m)	CIMMYT ($ m)	University of Sydney ($ m)	Present value of CSIRO ($ m)	Present value of CIMMYT ($ m)	Present value of University of Sydney ($ m)
1995	3.4	0.2	0.2	13.0	0.8	0.8
1996	3.4	0.2	0.2	12.1	0.7	0.7
1997	3.4	0.2	0.2	11.3	0.7	0.7
1998	3.4	0.2	0.2	10.6	0.6	0.6
1999	3.4	0.2	0.2	9.9	0.6	0.6
2000	3.4	0.2	0.2	9.3	0.6	0.6
2001	3.4	0.2	0.2	8.6	0.5	0.5
2002	3.4	0.2	0.2	8.1	0.5	0.5
2003	3.4	0.2	0.2	7.6	0.5	0.5
2004	3.4	0.2	0.2	7.1	0.4	0.4
2005	3.4	0.2	0.2	6.6	0.4	0.4
2006	3.4	0.2	0.2	6.2	0.4	0.4
2007	3.4	0.2	0.2	5.8	0.3	0.3
2008	3.4	0.2	0.2	5.4	0.3	0.3
2009	3.4	0.2	0.2	5.0	0.3	0.3
2010	3.4	0.2	0.2	4.7	0.3	0.3
2011	3.4	0.2	0.2	4.4	0.3	0.3
2012	3.4	0.2	0.2	4.1	0.2	0.2
2013	3.4	0.2	0.2	3.8	0.2	0.2
2014	3.4	0.2	0.2	3.6	0.2	0.2
2015	3.4	0.2	0.2	3.4	0.2	0.2
Total	**70.4**	**4.2**	**4.2**	**150.4**	**9.0**	**9.0**

Benefits to 2025

The benefits calculated in the analysis are the net benefits from CSIRO's Cereal Rust program, that is, the difference between the "with" and "without program" scenarios (as shown in Table 6). The analysis is equivalent to carrying out separate analyses for the "with program" and "without program" scenarios and calculating the difference between them.

The steps in quantifying the gains from CSIRO's Cereal Rust program are as follows:

1. Combine annual benefits produced from resistance (Table 5) in each year with the attribution ratio due to the program, to get an estimate of the value of disease control that year. This gives an estimate of the economic value of disease control for stripe rust in wheat from the program for that year and all subsequent years (Table 8).

2. All past benefit flows from 1995 to 2015 were adjusted to real dollars using the CPI with base =100 at 2015. All benefits after 2015 were expressed in 2015-16 dollar terms. All costs and benefits were discounted to a present value using a real discount rate of 7% (Table 8).

Table 8: Analysis of Benefits and Costs of CSIRO Rust Resistance Research (in 2015 prices)

Year	Benefits from the program				
	Benefits of stem rust control ($m)	Present value of benefits ($m)	Benefits attributed to CSIRO ($m)	Benefits attributed to collaborators (CIMMYT and University of Sydney) ($m)	Present value of total net benefits ($m)
1995	0.0	0.0	0.0	0.0	-14.5
1996	0.0	0.0	0.0	0.0	-13.6
1997	0.0	0.0	0.0	0.0	-12.7
1998	0.0	0.0	0.0	0.0	-11.9
1999	0.0	0.0	0.0	0.0	-11.1
2000	0.0	0.0	0.0	0.0	-10.4
2001	0.0	0.0	0.0	0.0	-9.7
2002	0.0	0.0	0.0	0.0	-9.0
2003	0.0	0.0	0.0	0.0	-8.5
2004	0.0	0.0	0.0	0.0	-7.9
2005	0.0	0.0	0.0	0.0	-7.4
2006	26.4	48.6	38.9	9.7	41.7
2007	26.4	45.4	36.3	9.1	38.9
2008	26.4	42.4	33.9	8.5	36.4
2009	26.4	39.6	31.7	7.9	34.0
2010	26.4	37.0	29.6	7.4	31.8
2011	26.4	34.6	27.7	6.9	29.7
2012	26.4	32.4	25.9	6.5	27.8
2013	26.4	30.2	24.2	6.0	25.9
2014	26.4	28.3	22.6	5.7	24.2
2015	26.4	26.4	21.1	5.3	22.7
2016	26.4	24.7	19.7	4.9	24.7
2017	26.4	23.1	18.5	4.6	23.1
2018	26.4	21.6	17.2	4.3	21.6
2019	26.4	20.2	16.1	4.0	20.2
2020	26.4	18.8	15.1	3.8	18.8
2021	26.4	17.6	14.1	3.5	17.6
2022	26.4	16.4	13.2	3.3	16.4
2023	26.4	15.4	12.3	3.1	15.4
2024	26.4	14.4	11.5	2.9	14.4
2025	26.4	13.4	10.7	2.7	13.4
Total	528.3	550.5	440.4	110.1	382.1

The flows of costs and benefits from 1995 to 2025 are used to calculate investment criteria. Investment was estimated for both total investment and for the CSIRO investment alone as reported Table 9 and 10.

Table 9: Results of CSIRO Investment and Benefits to CSIRO

Criteria

Present value of costs ($m)	150.4
Present value of benefits ($m)	440.4
Net Present Value (NPV) ($m)	290.0
Benefit-cost Ratio (BCR)	2.9

Table 10: Results of Total Investment and Total Benefits

Criteria	
Present value of costs ($m)	168.4
Present value of benefits ($m)	550.5
Net Present Value (NPV) ($m)	382.1
Benefit-cost Ratio (BCR)	3.3

Distribution effects on users

The benefits identified from the investment are predominantly private, namely benefits to wheat breeding companies and wheat growers both in Australia and overseas. For example, these markers are being used internationally through the international distribution network of CIMMYT. Although distribution effects were not considered to be a significant issue, a number of such effects may be worth considering. This includes the fact that the majority of the benefits identified accrue to wheat breeding companies and wheat growers both in Australia and overseas. These benefits allow them to either increase production levels, or reduce costs for the same level of production. There are potentially significant differences in the impacts on wheat breeding companies and wheat growers.

Externalities or other flow-on effects on non-users

In terms of flow-on effects, some of the benefits assigned to wheat growers and breeding companies will be shared along the input supply and market supply chains, including both domestic and foreign consumers. There may be some small potential benefits to foreign consumers of Australian wheat.

7 Sensitivity analysis

While the prospects look promising, the adoption of CSIRO's genetic markers in the wheat industry is by no means certain. For example, the adoption of CSIRO's DNA markers for breeding wheat varieties remains a key area of uncertainty. While industry consultation provides some narratives of the overall adoption, there is no reliable information on the actual adoption and performance of improved wheat varieties across Australia over time. In addition, the value of disease control figures is assumed to be constant for the full duration of the project life to 2025. It is likely that the number of incidences and level of severity could be different each year, which results in variable economic values of disease controls each year.

Given these uncertainties, it would be useful to look at results under different attribution rates and economic values of disease controls. NPV and benefit cost ratio calculations are particularly sensitive to changes in underlying parameters, so it is important to understand the results in perspective. In this section, we analyse the impact of variations in the discount and attribution rates as well as the value of rust control on the benefit and cost stream coming out of our central case.

As part of our sensitivity analysis, the value of disease control for rust was decreased and increased by 10 per cent. In addition, the estimated attribution rates were adjusted to test the impact of possible lower and higher values on the NPV. In the case of the benefits attributable to CSIRO markers, the attribution ratio was increased and reduced by 5 per cent. This change reflects how CSIRO markers might contribute to the breeding program. The results of the sensitivity analysis are shown in Table 11.

Table 11: Results of sensitivity analysis (CSIRO investment)

Assumption	Central assumption	Low assumption	High assumption	BCR (Central)	BCR (low)	BCR (high)
Discount rate (%)	7	5	10	2.9	3.6	2.2
Benefits attributable to CSIRO (%)	80	70	90	2.9	2.6	3.3
Benefits attributable to breeding (%)	93	83	100	2.9	2.6	3.7
Benefits attributable to markers (%)	20	15	25	2.9	2.2	3.7
Value of disease control for rust ($m per year)	540	432	648	2.9	2.3	3.5

Table 11 highlights the influence on our analysis of changes in key assumptions. We observed that NPV and benefit cost ratio calculations are particularly sensitive to changes in the discount and attribution rates. For example, a 10 per cent discount rate yielded a lower benefit cost ratio (2.2) compared to a 5 per cent discount rate (3.6). Similarly, an attribution rate of 90 per cent to CSIRO indicated that the benefit cost ratio (3.3) was much higher than in the low case (2.6).

While the parameters used in the base-case scenario seemed reasonable in the light of current realities on the ground, it was nevertheless important to test the robustness of our conclusions to variations in these assumptions. The low and high alternative assumptions used in the above sensitivity analysis were brought together to estimate benefit and cost streams under pessimistic and optimistic scenarios by combing changes across all variables jointly. The results under these different assumptions are summarised in Table 12.

Table 12: Alternative assumptions for sensitivity analysis (CSIRO investment)

	Pessimistic	Central (baseline)	Optimistic
Discount rate (%)	10	7	5
Benefits attributable to CSIRO (%)	70	80	90
Benefits attributable to markers (%)	83	93	100
Benefits attributable to breeding (%)	15	20	25
Value of disease control for rust ($m per year)	432	540	648
Benefit cost ratio	1.0	2.9	6.5

The pessimistic and central (baseline) scenarios perhaps offered conservative yet realistic forecasts of future benefits. In this we estimated that the benefit cost ratio is between 1.0 and 2.9.

8 Limitations and Future Directions

This evaluation is being undertaken using a mixed method to evaluate the research impact arising from the Cereal Rust research. In cases where the impacts can be assessed in monetary terms, a cost-benefit analysis (CBA) is used as the primary tool for evaluation. As a methodology for impact assessment, CBA relies on the use of assumptions and judgments made by the authors. This relates to economic indicators for the value of rust control, attribution and counterfactual. These limitations should be considered when interpreting the above analytical results.

Given the scope and budget for the analysis, we acknowledge that there are some limitations with regard to the evidence base of impacts. For example, it is unknown if or to what extent that breeding companies have adopted CSIRO markers. It is also not clear whether new wheat varieties adopting CSIRO makers will be immune to new emerging rust such as Ug99 stem rust. In addition, reduced adverse environmental impacts, protection of employment and increased sustainability of rural communities were noted but not quantified due to the lack of reliable data.

We understand that research impact evaluation is an evolving practice and suggest that as part of its evolution, it needs to address some key data constraints by planning for impact and monitoring progress towards it. It is also important to engage with customers and other stakeholders to collect data/information and ensure a robust and thorough investigation of the outcomes and impacts.

9 References

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