

# **An economic evaluation of the osmoregulation gene technology to the Australian wheat industry**

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## **Abstract**

Episodes of rainfall irregularity and soil moisture deficit have focused attention on the widespread limitation of water supply on winter cereal crop production in Australia. This has motivated a number of efforts at breeding for improved drought tolerance. A recent example involves a cellular adaptation which mitigates water loss through solute accumulation (osmoregulation or osmotic adjustment). An assessment of the performance of osmoregulation yield response in the presence of climate change found that wheat cultivars with this gene are unlikely to be adversely affected by hotter and drier conditions across the wheat belt. The results of an economic evaluation of potential future innovations (wheat cultivars) from the osmoregulation gene technology are that for Australia the net present value could range from \$388 million to \$3.6 billion, depending on the adoption of wheat cultivars with the gene. Associated benefit-cost ratios ranged from 43:1 to 390:1, and internal rates of return were 16% to 27%. Even under pessimistic assumptions the returns are quite healthy. For NSW-only adoption, internal rates of return ranged from 10% to 22%. This osmoregulation technology has the potential for inclusion in wheat cultivars bred for other purposes, and for other crops. As such it has implications for agricultural plant breeders and farmers both in Australia and overseas, and there are substantial potential spillover benefits.

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Key words: Economic evaluation, wheat breeding, osmoregulation

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## Introduction

Episodes of below average rainfall, as in 2002, focus attention on the widespread limitation of water supply on winter cereal production in Australia. This has motivated a number of efforts at breeding for improved drought tolerance. One recent example involves a cellular adaptation which mitigates water loss through solute accumulation (osmoregulation or osmotic adjustment). Osmoregulation is a response to water stress, involving intra-cellular solute accumulation in response to a fall in extra-cellular water potential (Morgan 2002).

Work on osmoregulation began at Tamworth, NSW, with the discovery of large genotypic differences in wheat for this trait (Morgan 1977). Subsequent work examined a possible physiological basis for yield effects (Morgan 1980) and measured yield effects in the field (Morgan 1983). These were found to be dependent on the interaction of evaporative demand and soil water supply (Morgan 2000). Evidence of simple inheritance, present in the initial findings, was confirmed in more formal analyses (Morgan 1983, 1991). A single gene and chromosomal location was identified (Morgan 1991) and the arm position estimated (Morgan and Tan 1996).

Application to commercial plant breeding was evaluated, with development of a simple pollen test for the osmoregulation (*or*) gene (Morgan 1999) and release of Mulgara, the first commercial cultivar bred specifically for the *or* gene. Investigations of breeding application involving evaluation of the technology in a large number of field experiments – 187 over a period of 9 years in addition to a series of rainshelter experiments at the one location over 4 years in northern NSW (Morgan *et al.* 1986, Morgan 1995, 2000).

Advantages of osmoregulation are apparent when water demand exceeds water supply, especially in dry periods. Given recent information relating to projected climate change, assessments of the potential contribution of osmoregulation to agricultural production have been evaluated for a future climate scenario in the wheat growing period of the year. These have been examined using a simple model (Morgan 2000), and the implications for this analysis were used to derive likely yield impacts in the presence of climate change.

This paper contains an evaluation of the potential benefits from using the *or* technology in wheat, where the gene is known to be present in a number of cultivars. Genotypic differences in osmoregulation have also been found in other crop species, such as sorghum, chickpeas, soybean and barley (Morgan 2003).

A key issue is the potential for the single *or* gene to be used in breeding new wheat cultivars, and confer drought tolerance along with other characteristics for which they might be selected. There is considerable potential from use of this technology, depending on the frequency of current cultivars in which the gene is not present. Around 77% of current cultivars are in this category; these are the focus of this paper.

The paper proceeds by investigating potential yield increases within NSW and then extending the analysis to the whole of Australia. Annual potential benefits based on full adoption are estimated for each case and then the analysis considers the effects of different adoption patterns. The resulting benefits are set against the costs of technology development, and financial measures are calculated.

### **Economic theory context**

In terms of neo-classical economic theory and the welfare gains from new technologies (Alston *et al.* 1995), the approach used here assumes that supply is perfectly inelastic and demand perfectly elastic. Extra yield and production due to the technology are valued at the same price and all benefits are assumed to accrue to producers. This approach excludes the welfare triangle, but is considered to be a reasonable representation of the industry welfare change for a technology such as osmoregulation. Alston *et al.* (1995) concluded that this method generally provides a reasonable approximation of total industry benefits from innovations.

### **Methods of estimating yield changes**

The method of evaluation in this paper involves: (a) estimating yield advantages associated with *or* for climatic averages of wheat growing regions throughout NSW and Australia (Commonwealth of Australia, Bureau of Meteorology 2003); (b) making judgements about the likely extent and rate of adoption of the technology, and the time period for which it is expected to last; (c) quantifying aggregate benefits based on a set of prices; and (d) setting these benefits against the relevant costs, so that appropriate financial return measures can be derived.

### *A modelling analysis for Australia*

The analysis utilises regions defined and used by the Grains Research and Development Corporation (GRDC) for description and categorisation of wheat production (ABARE 1999). The yield increases for the various regions were determined using the model and results in Morgan (2000), as well as from additional sites. The model requires soil water holding capacities, mean temperatures, evaporation, rainfall to calculate phenology, and the ratio of evaporative demand to soil water supply for the period of net positive growth. This ratio is then used to estimate the relative yield response (yield of lines with high osmoregulation divided by yield of lines with low osmoregulation) using an empirical relationship based on field experiments in 5 seasons. Within each region the sites used to estimate response were limited by availability of appropriate climatic averages. The analysis assumes a uniform optimal sowing time of May 13 based on Gomez-Macpherson and Richards (1995) and maximum available soil water at sowing. Because the benefits from this work will be felt into the future, and in light of predicted future changes in climate, an analysis is first conducted to look at the implications of these possible changes.

The climate change scenario in CSIRO (2001) predicts hotter and drier conditions in the future across the wheatbelt, and the issue is how such changes might affect crop water stress and yield for a genetic technology based on improved osmoregulation within the wheat plant. The climate inputs for the osmoregulation yield model (Morgan 2000) of rainfall, evaporation and mean daily temperature were provided for the reference year (1990) by the Bureau of Meteorology for 15 sites across Australia. The increases in temperature (mean 1.05°C) and decreases in rainfall (mean 5.4%) are approximate mid-range values obtained from CSIRO projections for winter and spring 2030 (CSIRO 2001). Evaporation increases (mean 3.8%) were derived from the projected annual average change in the moisture balance.

Although the projected climate change produces hotter and drier conditions across the wheatbelt, its effect on crop water stress and osmoregulation yield response was negligible compared to the geographic variation (Morgan 2003). In fact, of the

responsive sites slight reductions occurred with climate change at all except Merredin, Wongan Hills and Ongerup, where responses increased. Greater reductions in winter rainfall are predicted in the WA wheatbelt (and a sustained reduction has indeed occurred since 1970). Overall the mean estimated yield increase for 2030 (19%) was virtually the same as for 1990 (20%).

The surprising absence of a climate change effect occurs because, with winter crops, increased temperature hastens development. In general, a 1 degree increase in temperature reduces time from sowing to flowering by 9 days. This reduces the in-crop evaporation substantially more than the rainfall and it approximately offsets the projected increase in evaporation and reduction in rainfall caused by climate change. Earlier flowering times would be agronomically possible because the period of frost risk would also be reduced, possibly by a similar time period.

In view of the absence of an effect of climate change, the economic analysis may be performed on either actual experimental data or modified responses for varying locations in the wheatbelt.

#### *Experimental and modelled responses for NSW*

The experimental dataset was for the northern wheat belt of NSW. It comprised two groups of 56 and 131 experiments for the periods 1980–1983 and 1997–2001, respectively (see Table 1). The results for the first set were published in Morgan *et al.* (1986) and the second in Powell (2002). The second publication deals with NSW Agriculture annual regional trials, which include the cultivars Mulgara and Sunco. Mulgara (line JM73) is a triple backcross derivative of Sunco, having been bred by selection for high osmoregulation using pollen grain expression (Morgan 1999). The yield comparison provides a reasonable estimate of the *or* gene effect (Morgan 2000).

The modelled data from Morgan (2000) for long-term average conditions used 7 locations in the NSW wheatbelt. This gave a long-term average yield advantage of 12%, broadly in agreement with but somewhat greater than the experimental results of 8% at 3.5 t/ha for the northern wheatbelt (Table 1). However, this value of 12% is appropriate for the experimental results based on a lower average yield of 2.07 t/ha for 2000-01 and 2001-02 in Table 2 (Morgan 2004). The average wheat yield in NSW was 1.94 t/ha in the 1990s decade (source: AWB website: [www.awb.com.au/AWBL/Launch/Site/AboutAWB/Content/CommunityEducation](http://www.awb.com.au/AWBL/Launch/Site/AboutAWB/Content/CommunityEducation)). Without breeding for the gene, it occurs in only approximately 23% of Australian varieties (Morgan 2001). There is therefore considerable scope for improvement in this gene.

#### *Without-project scenario*

An important issue in evaluating returns from R&D is the recognition of, and accounting for, what is likely to have happened if the work had not been done, i.e. whether the same advances would have been made by other workers perhaps at a later date. This is the definition of a ‘without-project’ scenario. Marshall and Brennan (2001) discussed evaluation of the economic impact of a single research project in terms of its costs and benefits in what is normally a broader research effort. In particular they were concerned about the inputs from other projects that contribute to the achievement of advances in the particular research project. These can be termed technological or farmer-generated ‘spill-ins’.

In the case of the *or* gene, the R&D has comprised a broad program of work over many years, as outlined above. It is conceivable that someone else could have conducted such a program at some other time, but there is no evidence of a long term program involving breeding for this trait in Australia or elsewhere in the world. The key prerequisites for commercial breeding, namely genetic differences, yield relationships (including physiology), genetics and linkages, and a simple method of gene identification are all original work conducted at Tamworth. Therefore the without-project scenario is that the work would not have been done and the total potential industry benefits estimated here accrue to the *or* R&D program.

### **Benefit estimation and adoption patterns**

The approach to benefit estimation involved using model-predicted field-level yield increases and farm-gate prices to estimate improved returns per ha for different regions of NSW and Australia. There are no extra farm-level costs associated with growing the wheat cultivars which include the *or* gene. These per ha financial benefits were then aggregated to represent NSW and national financial benefits at full adoption. Further assumptions about possible adoption patterns were also imposed.

The expected production increase within NSW, based on the average yield for the period 2000-02, the expected full yield increase (12%) for average climate conditions (with no climate change impact), and adjusted for the gene frequency (assuming no intentional breeding for the gene) is estimated to be 665, 000 t, as shown in Table 2. This is based on complete adoption of the *or* technology in NSW.

At the national level, the GRDC agro-ecological zone classification for Australian crop production (ABARE 1999) was used as a detailed wheat industry representation for benefit estimation, since the yield impacts of the *or* gene have been shown to vary with climate and region. Table 3 contains estimates of wheat area harvested, wheat production and average wheat yield for the average of the years 2000-2002. These figures were used as a basis for benefit estimation in future years of wheat varieties containing the *or* gene.

The model developed from NSW data was used to predict average wheat production impacts due to the *or* gene for locations throughout the Australian wheatbelt. At various sites in the Australian wheatbelt information on soil type, water holding capacity and the ratio of evaporation to soil water supply was used to calculate the percentage yield increase due to the osmoregulation technology. These percentage changes were adapted to the GRDC Agroecological Zones and are also shown in Table 3. These percentage changes are larger than the 12% for NSW because the biggest responses to *or* are in drier areas of SA, Victoria and WA.

When applied to the production figures in the table and after adjusting for *or* gene frequency in other cultivars, the potential annual increase in aggregate production at full adoption is in the order of 2.5 million tonnes of wheat across the whole country.

Extra wheat production in the field was valued at farm-gate prices to generate on-farm financial benefits. Estimates were made of the average proportion of wheat production by pay grade in Australian states over the 5-year period to 2001, and these are presented in Table 4. Wheat prices for December 2003 (\$/t FOB, GST exclusive)

from the AWB website (<http://www.awb.com.au>) for Prime Hard (\$240), Hard (\$229), Premium White (\$221), ASW (\$209) and Other (\$220) were used, with an average \$60 deduction for transport and FOB costs. Information on the wheat grades grown in each state is shown in Table 4. The price used to value extra production in each state and region was calculated as a weighted average of the above prices and the wheat grade proportions in Table 4.

#### *R&D costs*

This program of work has not been conducted by a large R&D group with associated infrastructure and other costs. The development and testing of the *or* gene and the associated release of a new variety and pollen test has been largely conducted since 1975 by one officer with technical support and NSW Agriculture inputs to trials in various locations. Industry funds have been only a minor contribution.

Past costs were derived using estimated full-time equivalent personnel numbers valued at current salary and on-cost rates. Other inputs were developed based on recollections of the scale and source of inputs used. The resulting amounts were adjusted by a GDP deflator and time preference of 4%. Similarly, future inputs to 2030 were estimated for trialling and extension programs; these were also discounted.

Future costs of cultivar development were equivalent to one technical officer plus on-costs and operating (\$10 000 per annum) per mainland state from 2004 to 2030. These costs should not be high because of the existence of the pollen test which can be carried out at the same time as cross fertilisation. Also, with a single gene, as material is produced with higher gene frequency there is less need to test for parentage. The net present value of all these inputs was estimated to be \$9.3 million and \$4.7 million for Australia and NSW in year 2003 terms.

#### *Adoption patterns*

The question for R&D benefit estimation also includes the issue of representing possible future adoption patterns, assuming that the predicted yield benefits will lead to demand for new cultivars and uptake of the technological innovation. The adoption of wheat cultivars which include the *or* gene is likely to vary according to climate; their value will be greater in drier areas.

The analysis used 2003 as the base year for financial calculations. All potential benefits were assumed to terminate in 2030. Beyond this time the basis for wheat production in Australia was considered to be sufficiently uncertain that further quantification was not warranted.

There is evidence of the lag between agricultural research project initiation and adoption of innovations being a minimum 10-year period (Cox *et al.* 1997, Marshall and Brennan 2001). Due to the development work already carried out the *or* technology is now available to wheat breeders, but the time period for breeding, trialling and releasing a new cultivar is likely to be of the order of 5-6 years (the Mulgara cultivar was released after 8 years). In light of this, two lag periods to adoption were used – 5 and 10 years.

Marshall and Brennan (2001) discussed how R&D projects contribute to advances and innovations. The project contributes to an advance which can provide an input to

the production of innovations. Their point was to ensure that the costs of developing the innovation are included when evaluating the potential benefits from an R&D project. In the present case the advance is the isolation and confirmation of the *or* gene (including the development of a pollen test), and the innovation is the development of cultivars (like Mulgara) adapted to particular regions in Australia. We have tried to incorporate both the past costs of achieving the advance and the likely future costs of developing innovative wheat cultivars throughout NSW and Australia.

A linear adoption pattern was utilised (Marshall and Brennan 2001), which was characterised by a lag to commencement of adoption, a period of linear adoption and a maximum (or ceiling) level of adoption. There was no limit placed on the period for which the technology was maintained at its ceiling level beyond the overall time restriction of 2030. The nature of the *or* technology is that it is a single gene which, once selected, can be maintained indefinitely while other genetic advances can be pursued. Hence the *or* technology will not be superseded in the current breeding and genetic framework for developing wheat cultivars.

Scenarios evaluated were lags to adoption of 5 and 10 years, time to adopt of 5, 10 and 15 years, and levels of adoption of 20%, 50% and 80%.

### **Economic results**

If the *or* gene can potentially be incorporated into wheat varieties that are adaptable in NSW and throughout Australia then the possible benefits from this technology are very large. The results of the economic evaluation reflect this, especially since the R&D costs are quite small. There are no extra farm production costs assumed for cultivars which might be developed with this gene.

The main results are shown in Table 5, where the Net Present Value is presented (in units of 2003 \$'million) for both NSW and Australia at a real discount rate of 4%. Depending on assumptions for lag to adoption, time to adopt and level of adoption the NPV ranged from \$101 million to \$958 million for NSW, with associated BCRs of 22:1 and 204:1 and IRRs of 10 and 22%, respectively. For Australia the NPVs ranged from \$388 million to \$3.6 billion, with associated BCRs of 43:1 and 390:1 and IRRs of 16% and 27%, respectively.

In these results the NPV and BCR figures appear to be relatively high compared to the IRRs. The reason for this is that the period of R&D inputs is relatively long compared to the later (shorter) period of annual benefits. This is a characteristic of the IRR measure and is a reason why all three financial return measures should be considered.

Two sensitivity analyses of these results were performed for Australia. They involved using a different base for the production figures used to project future benefits, and considering the effects of reducing the potential yield advantage from the *or* gene from 12% to 8%. The 8% yield increase was from the measured changes from experimental data presented in Table 1. The production figures in Tables 2 and 3, which were averages for the first years of the 2000 decade, were replaced with averages from the 6 years 1992-93 to 1997-98, which was the original data series presented in ABARE (1999) for the GRDC agroecological zones. For all Australia the average wheat production was reduced from 22.027 million tonnes (Table 3) to 15.704 million tonnes, and the average Australian yield was reduced from 2.1 t/ha to

1.8 t/ha. These lower figures provide a more conservative estimate of the potential benefits from the technology.

The sensitivity results presented in Table 6 indicate that for Australia when 1990s production figures are used as a base, the NPV varied from \$263 million to \$2.5 billion, with associated BCRs of 29:1 and 268:1 and IRRs of 14% to 25%, respectively. With a lower yield increase and the 2000s production figures, the NPVs ranged from \$206 million to \$2.0 billion, with associated BCRs of 23:1 to 212:1 and IRRs of 14% to 24%, respectively.

## **Discussion**

Potential benefits from the advance in plant breeding associated with the *or* gene technology are substantial if innovative wheat cultivars can be developed in the future. The NPV figures from this evaluation are substantial if the technology is adopted at high levels across Australia, where a 12% yield improvement based on current production and yield levels could provide industry benefits from \$388 million to \$3.6 billion in 2003 dollar terms. The associated BCRs are very large, since the costs have been relatively small, and the IRR figures range from 16 to 27%. At lower levels of potential yield improvement and lower production levels as a base for projection the Australian results are still very positive.

Even if the benefits are confined to NSW the figures are still very healthy. The most pessimistic adoption and yield improvement scenario in NSW still returns an NPV of \$101 million, a BCR of 22:1 and an IRR of 10%. These are substantial figures for essentially the work of one professional officer.

These results can be considered in light of Alston *et al.* (2000) who considered ranges of rates of return from a large sample of evaluation studies. For research-only studies, their results showed that (excluding outliers) the distribution of IRRs had a mean of 79.6%, a mode of 26% and a median of 49%. The above results for Australia compare favourably with this distribution. The IRR figures in this analysis may be affected by long costing periods.

Another issue for this technology is that there are substantial spillovers of benefits to wheat breeding in other countries and to other crop species (sorghum, chickpeas, soybeans, barley and Brassicas). These effects have not been included in this analysis and, as Alston (2002) has noted, this is likely to have underestimated the returns from this R&D program substantially.

We conclude that a relatively conservative evaluation of the *or* gene technology, if used to generate new wheat cultivars across a variety of geographical regions in Australia, is likely to earn substantial industry benefits from the investment in the particular R&D program over the past 40 years by the NSW Government. This technology is not likely to be adversely affected if the climate changes as some suggest. The work has implications for agricultural plant breeders and farmers both in Australia and overseas, and there are substantial spillover benefits likely to accrue to other industries and societies.



**Table 1. Measured and calculated (climate data) yield increases due to the *or* gene for NSW**

Period	No. of trials	Mean yield (t/ha) (a)		Yield gain t/ha	% increase
		With	Without		
1980 - 1983	56	3.36	3.04	0.32	10
1997 - 2001	131	3.56	3.37	0.20	6
All	187	3.46	3.21	0.26	8
Long term	modelled				12

(a) With and without the *or* gene

**Table 2. Expected increase in production for NSW due to full application of the *or* breeding technology**

Average yield 2000-01 to 2001-02 (a) t/ha	Increase due to osmoregulation t/ha	Adjusted increase(b) t/ha	Average area of production (a) 2000-01 – 2001-02 '000 ha	Increased production '000 t
2.07	0.24	0.18	3696	665

(a) Source: AWB website

(b) Adjusted for *or* gene frequency

**Table 3. Summary of Australian wheat areas sown, production and yield by GRDC Agroecological Zone, average of years 2000 – 2002, and percent yield change due to *or* gene**

Zone name	Area harvested (a)	Wheat production (b)	Average yield (c)	Yield increase due to <i>or</i> gene (d)
Qld Central	51	98	1.9	+30
NSW NE/QLD SE	842	2001	2.4	+5
NSW NW/QLD SW	844	1574	1.9	+20
NSW Central	1233	2980	2.4	+21
NSW VIC Slopes	609	1913	3.1	+12
VIC HR/TAS	79	279	3.6	0
SA VIC Bordertown- Wimmera	486	1458	3.0	0
SA VIC Mallee	1487	2588	1.7	+50
SA Midnorth-Lower Yorke, Eyre	787	2015	2.6	0
WA Sandplain	261	454	1.7	+66
WA Northern Zone	1330	2031	1.5	0
WA Eastern Zone	668	954	1.4	+24
WA Central Zone	2029	3680	1.8	+3
<b>Total</b>	<b>10704</b>	<b>22027</b>	<b>2.1</b>	

(a) Units of '000 ha

(b) Units of '000 t

(c) Units of t/ha

(d) Percent change in yield

Source: ABARE surveys

**Table 4. Estimates of proportions of wheat production by pay grade for states and Australia, based on 5 years to 2001**

	Wheat grade					Total
	<i>Prime hard</i>	<i>Hard</i>	<i>Premium white</i>	<i>Standard white</i>	<i>Other</i>	
	%	%	%	%	%	%
<b>Queensland</b>	34	43	15	7	2	100
<b>Northern NSW</b>	27	51	17	0	5	100
<b>Southern NSW</b>	6	36	25	27	6	100
<b>NSW</b>	14	41	22	17	6	100
<b>Victoria</b>	3	36	30	28	3	100
<b>South Australia</b>	3	37	32	26	3	100
<b>Western Australia</b>	0	37	35	27	1	100
<b>Australia</b>	8	39	28	22	3	100

**Table 5. Summary of economic returns from wheat breeding with the *or* gene**

NPV of benefits (2003 \$'million)										
		Time to adopt								
		5 years			10 years			15 years		
Ceiling		20%	50%	80%	20%	50%	80%	20%	50%	80%
<i>NSW</i>										
Lag to adoption (years)	5	236	598	959	198	502	807	164	418	672
	10	160	407	654	129	328	528	101	259	418
<i>Australia</i>										
Lag to adoption (years)	5	898	2259	3621	754	1900	3045	627	1583	2538
	10	611	1540	2470	492	1245	1997	388	984	1581

**Table 6. Sensitivity analysis of economic results for Australia, lower production figures and 8% yield advantage**

NPV of benefits (2003 \$'million)										
		Time to adopt								
		5 years			10 years			15 years		
Ceiling		20%	50%	80%	20%	50%	80%	20%	50%	80%
<i>1990s production base</i>										
Lag to adoption (years)	5	613	1547	2481	515	1301	2087	427	1083	1739
	10	416	1054	1692	335	851	1367	263	672	1082
<i>8% yield advantage</i>										
Lag to adoption (years)	5	483	1222	1961	405	1027	1649	336	855	1374
	10	327	832	1337	263	672	1082	206	530	854

## References

ABARE (1999), *Australian Grains Industry: Performance by GRDC Agroecological Zones*, ABARE Report Prepared for the Grains Research and Development Corporation, Canberra, April.

Alston, Julian M. (2002), 'Spillovers', *Australian Journal of Agricultural and Resource Economics*, 46(3): 315-46.

Alston, Julian M., Marra, Michelle C., Pardey, Philip G., and Wyatt, T.J. (2000), 'Research returns redux: a meta-analysis of the returns to agricultural R&D', *Australian Journal of Agricultural and Resource Economics*, 44(2): 185-215.

Alston, J.M., Norton, G.W. and Pardey, P.G. (1995), *Science under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting*, Cornell University Press: Ithaca and London.

Commonwealth of Australia, Bureau of Meteorology (2003), *Annual Climate Summary 2002*.

[http://www.bom.gov.au/media\\_releases/climate/change/20030106.shtml](http://www.bom.gov.au/media_releases/climate/change/20030106.shtml).

Cox, Thomas, Mullen, John and Hu, Wensheng (1997), 'Nonparametric measures of the impact of public research expenditures on Australian broadacre agriculture', *Australian Journal of Agricultural and Resource Economics*, 41(3): 333-60.

CSIRO (2001), *Climate projections for Australia*. CSIRO Atmospheric Research, Melbourne. <http://www.dar.csiro.au/publications/projections2001.pdf>.

Gomez-Macpherson, H. and Richards, R.A. (1995), 'Effect of sowing time on yield and agronomic characteristics of wheat in south-eastern Australia', *Australian Journal of Agricultural Research* 46: 1381-1399.

Marshall, Graham R. and Brennan, John P. (2001), 'Issues in benefit-cost analysis of agricultural research projects', *Australian Journal of Agricultural and Resource Economics*, 45(2): 195-213.

Morgan J.M. (1977), 'Differences in osmoregulation between wheat genotypes', *Nature* 270: 234-235.

Morgan J.M. (1980), 'Possible role of abscisic acid in reducing seed set in water-stressed wheat plants', *Nature* 285: 655-657.

Morgan J.M. (1983), 'Osmoregulation as a selection criterion for drought tolerance in wheat', *Australian Journal of Agricultural Research* 34: 607-614.

Morgan J.M. (1991), 'A gene controlling differences in osmoregulation in wheat', *Journal of Plant Physiology* 18: 249-257.

Morgan J.M. (1995), 'Growth and yield of wheat lines with differing osmoregulative capacity at high soil water deficit in seasons of varying evaporative demand', *Field Crops Research* 40: 143-152.

Morgan J.M. (1999), 'Pollen grain expression of a gene controlling differences in osmoregulation in wheat leaves. A simple breeding method', *Australian Journal of Agricultural Research* 50: 953-962.

Morgan J.M. (2000), 'Increases in grain yield of wheat by breeding for an osmoregulation gene: relationship to water supply and evaporative demand', *Australian Journal of Agricultural Research* 51: 971-978.

Morgan J.M. (2001), 'Osmoregulation gene (or) frequency in Australian and other wheat cultivars and accessions', Proc. 10<sup>th</sup> Assembly of the Wheat Breeding Society of Australia 10-13.

Morgan, J.M. (2002), 'The drought tolerance gene in Australian wheat cultivars – an overview' in Martin, Bob (Ed), *Research Update: Update of research in progress at the Tamworth Centre for Crop Improvement 2001*, NSW Agriculture.

Morgan, J.M. (2003), 'Impact of climate change on crop water stress and yield increases due to an osmoregulation (drought tolerance) gene in wheat' in Martin, Bob (Ed), *Research Update: Update of research in progress at the Tamworth Agricultural Institute 2002*, NSW Agriculture.

Morgan J.M. (2004), 'From process to production – the pursuit of understanding and commercial utilisation of osmoregulation to increase yield of wheat and other crop species under conditions of water stress', *Functional Plant Biology* (submitted).

Morgan J.M., Hare, R.A. and Fletcher, R.J. (1986), 'Genetic variation in osmoregulation in bread and durum wheats and its relationship to grain yield in a range of field environments', *Australian Journal of Agricultural Research* 37: 449-457.

Morgan, J.M. and Tan, M.K. (1996), 'Chromosomal Location of a Wheat Osmoregulation Gene Using RFLP Analysis', *Australian Journal of Plant Physiology* 23: 803-806.

Powell, C. (2002), 'Winter crop variety experiments 2001', NSW Agriculture, Orange.