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Antipodean agricultural and resource economics at 60: agricultural innovation

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Innovation in agriculture – itself an innovation some 10,000 years ago – is at the centre of many economic and social issues, either as a cause of problems or a solution to them. From the beginning, but especially over the past 150 years, innovation has transformed agriculture and in doing so has contributed to the transformation of whole economies. The consequences have been profoundly important for lives and livelihoods, generally favourable, but almost always with some undesirable consequences for at least some people. Economic and policy issues arise because agricultural research is subject to various market failures, because the resulting innovations and technological changes have important economic consequences for net income and its distribution among individuals and among factors of production, and because the consequences are difficult to discern and attribute among causes. These issues have been studied by economists and documented in the literature on the economics of innovation in agriculture that began as such in the 1950s, around the time of the creation of the Australian Agricultural Economics Society. Members of that nascent society were early contributors to this emerging field of study and have played disproportionately significant roles in it over the ensuing decades.

Key words: agricultural transition, productivity, R&D, technology.

1 Introduction

The nation of Australia was born on 1 January 1901, and by 1911, the total population was 4.5 million people, of whom around 43 per cent (1.9 million) were rural residents. A little over a century later, the total population had increased to 24 million people while the shares of GDP and employment attributable to agriculture shrank from around 25 per cent to just 2 per cent.[1]

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[1] In 1911, New Zealand was home to 815,862 people, increasing to 4.4 million by 2011. New Zealand's agricultural economy is much smaller than Australia's, but is a more significant share of that country's overall economy (22.8 per cent in 1949 down to 5.4 per cent in 2011).

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Agricultural innovation was pivotal to this remarkable transformation of the Australian economy, and organised agricultural science was a critical contributor to the innovation process (Gruen 1961-S, Lloyd 1986-S).[2] When the Australian Agricultural Economics Society (AAES) was founded in February 1957, about halfway through the nation's history since Federation, the process of agricultural transformation was well underway, but far from over. Many of the issues concerning the members of the fledgling Society over the years to come were associated with the agricultural transition and its consequences.

Policy issues arise because agricultural research is subject to various market failures, because the resulting innovations and technological changes have important economic consequences for net income and its distribution among individuals and among factors of production, and because the consequences are difficult to discern and attribute among sources. These issues have been studied by economists and documented in the literature on the economics of innovation in agriculture that began as such in the 1950s, with work by T.W. Schultz and others, around the time of the creation of the AAES. Members of that nascent society were early contributors to this emerging field of study and have played leading roles in it since.

In Australia, public sector agricultural R&D expanded after WWII (Mullen *et al*. 1996-S) and agricultural economics, as an element of that, really took off in the late 1960s and early 1970s. Much of this growth in agricultural economics was occupied with farm policy questions, but some of the growing capacity was spent on the economics of agricultural innovation. Around this time, the literature on modelling and measuring returns to research began to develop, as did a related literature on the economics of agricultural science policy.[3] In the period since then, we have seen some very significant changes in (i) the total funding for agricultural R&D, (ii) the roles of public- and private-sector entities in funding the work of universities and state and federal government agencies in carrying it out, (iii) the subject matter and disciplinary emphasis, and (iv) the involvement of economists in assisting with evaluation, priority setting and policy design.

Many have lauded the innovative Australian arrangements, but Inquiries by the Industry Commission (1995-S) and its successor Productivity Commission (2011-S) while endorsing evidence on the high returns to the investment have increasingly questioned the basis for the matching government support. Perhaps reflecting the same forces at work, during the past decade or two we have witnessed significant changes in support for agricultural science (and agricultural economics) within State and

[2] Citations designated with an "S" are included in Appendix S1 in the online supporting information.

[3] Public policies related to agricultural R&D and innovation were discussed briefly in the 1974 Australian government "Green Paper" on *Rural Policy in Australia* (Harris *et al*. 1974) and in more depth in the 1976 IAC report on *Financing Rural Research*, from the inquiry led by Alan Lloyd (IAC 1976).

Commonwealth government departments, and universities.[4] This has provided work, albeit along with some reduction in security of employment, for economists working on the economics of agricultural science.

The economics of agricultural science is a broad subject. In this review, we highlight the contributions made by economists from Australia and New Zealand to the development of economic thought and knowledge in studies of the consequences of investments in agricultural science.[5] As pointed out by Grant Scobie (2016 this issue), the work by Australians and New Zealanders contributing to this set of topics can be better appreciated in the context of the economics of innovation more broadly, both (i) generally, as reviewed, for instance, by the Productivity Commission (2011-S) relative to Australia, and in the volumes by Bronwyn Hall and Nate Rosenberg (2010-S) and (ii) in agriculture, as discussed in our chapter with Vernon Ruttan therein (Pardey *et al.* 2010) and in our article in the *Annual Review of Resource Economics* (Alston *et al.* 2009).

Space constraints preclude us from providing details here on that broader context and we must also limit the scope in other ways. We do discuss the contributions by Antipodean economists in studies regarding the adoption of farm technologies (Section 2), the consequences for productivity (Section 3), the implications for consumer and producer welfare (Section 4) and returns to the investment (Section 5). These contributions include work on developing and improving the concepts and methods of measurement, as well as employing them. A final section discusses the unfinished business (Section 6).

2 The adoption of farm technologies

The literature generally is heavily skewed towards assessing the returns to investments in the development and adoption of crop varietal technologies. However, an extensive adoption literature deals with a much broader set of Australian farm technologies. Parish (1954) investigated the adoption of various technologies used by NSW wheat farmers; Gruen (1960) – the benefit from pasture improvement in the wool industry; Wilkening *et al.* (1962-S) – the uptake of dairy-farming technologies and practices in Northern Victoria; Presser and Russell (1965-S) – the adoption of rabbit eradication

[4] These changes have entailed slowing and now declining real growth in funding and a shift to project-based, more competitive sources of support for agricultural science, generally. Many research positions for agricultural economists in government and universities have been eliminated and some of the departments or branches in which they worked no longer exist as such.

[5] In the online supporting information (Appendix S2), we explore these issues in more depth and in conjunction with a review of the history of Australia's agricultural science and technology policy. This review encompasses agricultural research institutions and investments, some economic analysis of these aspects, and some documentation of principal players among Australian agricultural economists and the roles they played both in shaping that economic history and in contributing to the history of economic thought. Jacobsen *et al.* (1998-S) review the evolution of agricultural research institutions and policy in New Zealand.

technologies; Duncan (1969), Menz (1984-S) and Vere and Muir (1986-S) – the uptake of improved pasture practices; Lindner *et al.* (1982) – the use of trace-element fertiliser; Findlay (1980-S) – the adoption of sale-by-sample methods by Australian wool growers; Llewellyn and Pannell (2009-S) – the use of weed management practices; Pannell and Vanclay (2011) – the uptake of land conservation practices; Brennan (2007-S) – policy influences on the adoption of efficient irrigation systems; and D'Emden *et al.* (2008-S) – the adoption of conservation tillage practices.

In related work, Sally Marsh and David Pannell with others have studied the role of extension in the context of adoption of various types of technologies, for instance in facilitating the adoption of lupins in Western Australia (Marsh *et al.* 2000a-S).[6] Beginning in 1999 and ending in 2008, the Australian Centre for International Agricultural Research (ACIAR) conducted a large number of assessments of the uptake of ACIAR-funded research results (http://aciar.gov.au/adoption).

Australasian economists have also contributed to our conceptual understanding of the determinants of and the processes associated with decisions to adopt new farming technologies. Bob Lindner developed and tested Bayesian-style, decision-theoretic models about the acquisition and use of information sourced on- and off-farm (Lindner *et al.* 1979-S, 1982-S, and Lindner and Gibbs 1990), while Jock Anderson and Derek Byerlee examined a related issue, the role of on-farm adaptation in the process of technology uptake and change (Byerlee and Polanco 1986-S, Anderson 1993, and Byerlee 1993).

A further important strand of the farm technology adoption literature concerns the extent to which risk affects the decision to use a new technology (Marra *et al.* 2003-S, and Abadi Ghadim *et al.* 2005), and how new technologies may serve to reduce the risk of farming (Anderson 1974-S, 1991-S); another strand relates to social attitudes to new technologies (Butler 1999-S, on adoption of rBST). Many of these ideas are captured and extended in the ADOPT model (Kuehne *et al.* 2013-S), designed to predict adoption and diffusion of specific agricultural technologies and practices (https://research.csiro.au/software/adopt/).

3 Measures and measurement of agricultural productivity

Crop yield estimates developed by state and federal statisticians constitute the earliest and most enduring productivity estimates for Australian agriculture. National and state average yields have been reported for all major crops since 1860. Much of the early farm management research conducted by Australian economists during the 1950s and 1960s used crop or animal yield response models and production function constructs to help optimise mainly farmer (Dillon and Anderson 1990-S) but sometimes scientific (Dillon 1966-S;

[6] The same authors, with others, have made more general, related contributions regarding the economics of extension and related policy (see, e.g., Abadi Ghadim and Pannell 1999; Marsh and Pannell 2000b-S, and Marsh *et al.* 2004). See, also, Mullen *et al.* (2000-S).

Davidson and Martin 1965-S, and Davidson *et al.* 1967) choices affecting (crop and animal) responses to new production possibilities.

Bryan Philpott and colleagues in the Agricultural Economics Research Unit at Lincoln College appear to have been the first in the region to move from single-input (typically land) to multi-input productivity measures for agriculture. Philpott and Stewart (1958) published the first series of New Zealand aggregate input, output and productivity accounts spanning the period 1922–1956, which were subsequently revised and extended to encompass 1921–1967 (Philpott 1966-S, Philpott *et al.* 1967, and Hussey and Philpott 1969-S; see also Johnson 1970-S, 1972-S).

In Australia, economists at the Bureau of Agricultural Economics (BAE) spearheaded the development of multifactor productivity estimates for agriculture around the same time. Gutman (1955) developed a comprehensive set of indexes of major categories of inputs and (net) outputs for Australian agriculture for the period 1921–1948, in a study Alan Powell (1969, p. 28) described as '… the most ambitious of its type to appear in Australia before or since'. Citing the early USDA work on agricultural productivity measurement (notably Loomis and Barton 1961-S), Saxon (1963) published the first set we could find of aggregate productivity accounts for Australia (spanning 1936–1963). Young (1971) used the Solow (1957-S) residual decomposition approach to investigate the aggregate productivity performance of Australian agriculture for the period 1948–1968, and Roy Powell (1974) developed a productivity series spanning 1920–1970.

A regular series of more formal assessments of the multifactor productivity performance of Australian agriculture began in the 1980s. Lawrence and McKay (1980) were the first to use Divisia-style index number methods to form Tornqvist-Theil input and output aggregates and multifactor productivity measures of the Australian sheep industry for the period 1952–1977. Since then, ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences) economists – led at different times by P.B. Paul, Tony Beck, Brian Moir, Denis Lawrence, Philip Knopke, Phil Kokic, Warren Males, Katarina Nossal, Yu (Eric) Sheng and Shiji Zhao – drew on various Australian Bureau of Statistics (ABS) databases and ABARES farm survey data to produce and assess an expanding and ever-updating set of aggregate input, output and multifactor productivity estimates for Australian broadacre agriculture and its crops, grains, beef and sheep production subsectors (e.g. Sheng and Jackson 2015-S). John Mullen, working with other colleagues (Mullen and Cox 1996) including those at ABARES (Sheng *et al.* 2010), has sought to make sense of the available data, reconcile the differences in estimates implied by data developed by the ABS versus ABARES and model productivity as a function of public research investments.[7] In parallel with the Australian evidence, beginning in the mid-1980s, Phil Pardey launched an ongoing effort involving Julian Alston and

[7] See Table S-2 in Appendix S4 in the online supporting information for a chronological listing of the Australian agricultural productivity evidence.

other (non-Australian) colleagues to develop an evolving series of estimates of U.S. state and national aggregate agricultural input, output and productivity indexes (see www.instepp.umn.edu/united-states).

Measurement matters are critical to a proper understanding of the sources of output growth in agriculture, and especially the unexplained or residual elements of that measured growth we call productivity (Griliches 1994-S). Craig and Pardey (1996) and Andersen *et al*. (2011-S, 2012a and b-S) address input quality change and the measurement of capital inputs into agriculture and its relation to the observed phenomenon of procyclical growth; Byerlee and Murgai (2001-S) discuss and Hoang and Coelli (2011-S) illustrate attempts to 'green' agricultural productivity accounts; Fischer *et al*. (2013-S) revisit and reassess the long literature on yield growth and yield gaps (see, also Beddow *et al*. 2014-S); Beddow and Pardey (2015-S) develop and apply new spatially explicit output indexing methods to assess the consequences of crop movement for output growth, while Sheng *et al*. (2015a-S) use farm-level data to measure the effect of reallocating resources among farms on industry-level productivity growth, and Sheng *et al*. (2015b-S) examine the relationship between farm size and productivity in Australian broadacre agriculture. Economists have debated a possible slowdown in agricultural productivity growth in Australia in recent years (Sheng *et al*. 2010, 2011), the United States (Alston *et al*. 2010) and elsewhere in the world (Alston *et al*. 2010b-S), and measurement issues are central to that debate.

Another strand of inquiry concerns the measurement methods themselves. Mullen and Cox (1996), Acquaye *et al*. (2003-S) and Alston *et al*. (2010) systematically examined the empirical implications of the choice of index number methods for the resulting input, output and productivity measures. Chris O'Donnell (2010 and 2012) has examined methods to decompose changes in indexes of total factor productivity (TFP) into their technical change and efficiency components, and Coelli and Rao (2005) used nonparametric methods to examine agricultural productivity performance worldwide (see, also Headey *et al*. 2010-S). An encompassing view of approaches to productivity assessment is provided by Tim Coelli, Prasada Rao, Chris O'Donnell and George Battese in their 2005 volume, *An Introduction to Efficiency and Productivity Analysis* (which was first published in 1998). This book offers a comprehensive overview of parametric and nonparametric approaches to productivity measurement, and these authors are widely regarded as authorities in the subject. They and others have published many papers applying especially the nonparametric approaches to many applications outside agriculture – for which they seem especially well suited – as well as some in agriculture, though mainly overseas (Coelli and Battese 1996-S).

4 Models of the size and distribution of research benefits

In the workhorse partial equilibrium model of research benefits, adoption of innovations causes an increase in supply (or a reduction in unit costs) for a farm commodity in a competitive market, and the benefits to producers and consumers are represented using Marshallian producer and consumer surplus measures. This economic surplus model, first introduced in relatively crude form by Schultz (1953-S) and Griliches (1958-S), underpins most if not all of the subsequent work on modelling and measuring the size and distribution of returns to research, and many related issues, at least conceptually.

Australian agricultural economists were among the first to adopt this approach and to begin to explore its attributes in the 1970s. Duncan's (1972) estimate of the economic returns to pasture improvement research programs is the first Australian study of its type, followed closely by Jim Ryan's (1975) assessment of the dairy herd improvement scheme operated by the NSW Department of Agriculture. Duncan and Tisdell (1971), Scobie (1976), Lindner and Jarrett (1978, 1980-S) and Rose (1980-S) explored the roles of functional forms and elasticities of supply and demand, and the nature of the research-induced supply shift for findings concerning the total benefits from research and its distribution, as reviewed by Davis (1981a,b) and Norton and Davis (1981). In their more recent review of this literature, Alston *et al.* (2009-S) discuss the main issues and present a model that nests both linear and constant elasticity models with parallel or proportional shifts – the main options in the literature.

The nature of the research-induced supply shift has been an issue of abiding concern because it is difficult to determine empirically and has significant implications for the size – and particularly the distribution – of research benefits. In *Science under Scarcity*, Alston *et al.* (1995) opted to apply a maintained hypothesis of a parallel shift, in which case the Griliches formula of $\text{GARB} = kV$ is a very good approximation (where GARB is gross annual research benefits, k is the proportional shift down in supply at the without-research price and V is the value of production). Martin and Alston (1997-S) discussed this approximation in the context of a cost-function approach, and Alston *et al.* (2010a-S, 2011-S), like many others, used it unashamedly in their study of U.S. agriculture. A related issue concerns the measurement of k, which is sensitive to the value of the elasticity of supply if data on yields or productivity gains are interpreted as providing an indication of an increase in supply in the quantity direction (Zhao *et al.* 1998). These issues continue to matter.

From the outset, Australian authors were conscious of the (small-country) open-economy implications of agricultural R&D and the attendant distributional questions (e.g. Duncan and Tisdell 1971). In their 1981 monograph on *Measuring a Country's Gains from Research: Theory and Application to Rural Australia*, Geoff Edwards and John Freebairn formally extended the analysis (i) to a multimarket setting by disaggregating either vertically (across stages of production or categories of inputs) or horizontally (to allow for inter-regional or international trade), and (ii) to allow for commodity market distortions resulting from government policies or market power of buyers or sellers. These extensions raise further issues related to where the innovation might take effect within the multimarket system, including international technology spillovers, and the implications for the size and distribution of research benefits. This work and further elaborations by Edwards and Freebairn (1982-S, 1984-S) and Freebairn *et al*. (1982-S, 1983-S) provide the conceptual groundwork for the multimarket and multicountry modelling framework laid out by Davis (1984-S) and Davis *et al*. (1987) for ACIAR and inspired the development of the vertical-cum-multimarket, equilibrium-displacement model (EDM) approach as applied, for example, by Mullen and Alston (1990).

Freebairn *et al*. (1983-S) assumed fixed proportions between the farm product and processing inputs. Alston and Scobie (1983) extended that analysis to the case of variable proportions, using a model owed to Muth (1964-S).[8] Variations on this model of research benefits have been applied extensively since then. This body of research has established conditions under which farmers are likely to capture a larger share of the benefits from traditional farm production research, compared with downstream research and promotion activities, and when the incidence of levies to fund research matches reasonably closely with the distribution of benefits (Donaldson 1964, Tisdell 1974). Much of this work has used numerical simulations because analytical solutions quickly become cumbersome as the model increases in size (Holloway 1989-S, Alston 1991-S, and Alston *et al*. 1995-S).[9] Zhao *et al*. (2000-S) and others have explored issues related to parameter selection and sensitivity analysis, which becomes intractable when many parameters are involved.

True computable general equilibrium (CGE) models, such as ORANI (www.copsmodels.com/oranig.htm) and GTAP (www.gtap.agecon.purdue.edu), have significant features in common with many of the smaller, more purpose-built EDMs, and these and other CGE models have been applied to evaluate the impacts of agricultural productivity change within Australia (Wittwer and Anderson 2001-S), in the context of international agricultural trade taking account of trade barriers (Anderson 2010-S, and Anderson and Jackson 2005-S), and in developing country contexts (Coxhead and Warr 1991-S and 1995-S, Coxhead 1992-S and 1997-S, Warr 2014-S, and Alston *et al*. 2014b-S).

Edwards and Freebairn (1981) raised the issue of research benefits in the presence of market distortions. Alston *et al*. (1988-S) built on their work to establish that (i) the main effects of price distorting policies are to change the distribution of benefits, and (ii) the total benefits from research in the presence of a price distortion are equal to the benefits from research in the absence of the distortion minus the effects of the research on the social costs

[8] Proportional changes in quantities and prices of inputs and outputs are expressed as linear functions of elasticities of input supply and output demand, input cost shares and the elasticity of input substitution.

[9] Examples include Mullen *et al*. (1988-S, 1989-S), Mullen and Alston (1990), Scobie *et al*. (1991) Alston and Mullen (1992-S), and Zhao *et al*. (2000-S).

of the distortion. Alston and Martin (1995-S) clarified why this latter result holds as a general second-best rule governing the total benefits from research in the presence of any distortion, and Alston *et al.* (1997-S, 1999-S) demonstrated this point in a Cournot oligopsony–oligopoly model.

5 Evidence on the economic consequences of agricultural R&D

Australasians have been active in quantifying agricultural research impacts at least since the early 1970s (Duncan 1972). The latest (version 3.0) InSTePP compilation of the global returns to R&D literature includes 2829 evaluations from 492 studies spanning the period 1958–2015 (see Hurley *et al.* 2016-S). It contains 57 studies of agricultural research carried out in Australasia, of which two were published in each of the 1970s and 1980s decades, jumping to 36 in the 1990s, and 17 thereafter (Table S-1).[10] These 57 studies reported a total of 216 evaluations; 26 (45.6 per cent) of which reported benefit–cost ratios (BCRs), 5 (8.8 per cent) internal rates of return (IRRs) and 26 (45.6 per cent) both BCRs and IRRs.[11]

Like the R&D evaluation literature generally, most of the Australasian evidence (113 evaluations, constituting 52.3 per cent of the total) assesses the economic returns to crop research. A significant share of that work highlights the economic benefits to Australia and New Zealand from research conducted elsewhere in the world, and most notably a series of assessments led by John Brennan of the spillover consequences of varietal improvement research conducted by the international agricultural research centres.[12] Byerlee and Moya (1993-S) placed a value on the spread of CIMMYT (International Maize and Wheat Improvement Center) wheat varieties throughout the developing world, Pardey *et al.* (1996-S) assessed the U.S. benefits from the local uptake of improved rice and wheat varieties developed by the CGIAR centres, while Pardey *et al.* (2006-S) valued the benefits to Brazil from the local uptake of rice, bean and soybean varieties developed with input from agencies elsewhere in the world. Scobie and Eveleens (1987) assessed the aggregate returns to agricultural R&D in New Zealand, as did Sheng *et al.* (2011-S) for Australia. As part of the ongoing awareness and resource mobilisation activities of the Crawford Fund, Tribe (1991-S) and

[10] Additional compilations and reviews of the returns to research evidence by Australian agricultural economists include Norton and Davis (1981), Alston *et al.* (2000, 2000b-S, 2009-S), Raitzer and Lindner (2005-S), Shanks and Zheng (2006-S), and Lindner *et al.* (2013-S).

[11] Australian economists have also generated substantial evidence on the returns to agricultural R&D elsewhere in the world, authoring an additional 130 rate of return studies (that report a total of 266 estimates) for research conducted in the United States, Brazil, Uruguay and India, for example. Thus, estimates of the returns to Australian agricultural R&D plus rest-of-world research estimates generated by Australian authors constitute 17 per cent of the evaluations in the InSTePP version 3.0 database.

[12] See, for example, Brennan and Fox (1995); Brennan (1986-S, Brennan 1989; 2007-S); Burnett *et al.* (1989-S); Brennan and Bantilan (1999-S); Brennan *et al.* (1997, 2002-S, 2003-S); and Brennan and Quade (2004-S).

Lawrence (1994-S) drew on this body of work, and its authors, to promote evidence-based advocacy for continued, and even expanded, Australian government support for domestic, bilateral and international agricultural research.

Australian economists have been at the forefront of efforts to improve the precision with which the benefits and associated research cost streams are estimated, and to make sense of the evidence – which sometimes beggars belief. In their formal meta review of the global body of evidence, Alston *et al*. (2000) associated the large dispersion in reported rates of return with differences in the attributes of the measures themselves (e.g. real versus nominal measures, ex post versus ex ante, average versus marginal, private versus social), the analysts, the research being assessed and, notably, details of the methodologies used to estimate the returns to research. Among the empirical issues identified are 'attribution' questions of three types: temporal, spatial and institutional (Alston and Pardey 2001). They also raised questions about the use of the IRR as a statistic of choice to summarise the reported research benefit and cost streams. As shown by Alston *et al*. (2011-S) and Hurley *et al*. (2014, 2014b-S), IRRs can lead to nonsensical results that are avoided by the use of a BCR or a modified internal rate of return.

Antipodean agricultural economists have made significant contributions to the conceptual understanding of these various attribution and measurement issues, developing improved data and empirical methods to better address the issues, and to developing improved measures as a result. The abiding bottom-line conclusion is that agricultural research continues to pay handsome dividends and we continue to invest too little in it in spite of extensive government intervention.

Much work on evaluating agricultural research investments has not sought to estimate a rate of return as such, but has used other metrics. This includes work on understanding the consequences of research and productivity change for poverty, nutrition, income distribution or the environment (Ryan 1977-S, Scobie and Posada 1978, Coxhead and Warr 1995-S, Anderson *et al*. 2005, Headey 2013-S, Alston *et al*. 2014a-S). It also includes some studies of benefits from more basic research and policy-oriented social science (Pardey and Smith 2004, Mullen 2005-S, Ryan and Garrett 2005-S, Walker *et al*. 2010-S), and reviews of entire research agencies or systems (most notably the impact study of the CGIAR system summarised in Anderson *et al*. 1988, and by Scobie 1979-S).

6 The unfinished agenda

Agricultural innovation and the policies that govern it matter for the wealth of nations and the well-being of individuals in the long run – especially the poor. The issues have been much studied and much has been learned, but important aspects related to both measurement and policy remain unresolved.

One perennial policy concern is the issue of too little funding for agricultural science in general, and especially certain types of science. Understanding why that is so and what can be done to fix it falls into the realm of wicked policy problems, like other issues relating to global public goods. Some of the dimensions contributing to this outcome may be more tractable but some component questions are inherently difficult.

A continuing conundrum is the apparent disconnect between evidence on the social payoff to agricultural innovation and the research that enables it, and producer, public and political perceptions. Effective communication about agricultural innovation and its consequences is not easy, and economists are not especially good at it. Issues here include not only disputes among economists about what the conventional summary statistics mean – conventional BCRs or IRRs versus MIRRs – but beyond that including whether money metric measures are sufficient. Further work is required to better understand the politics and political economy of public funding for agricultural science, and to develop more transparent, bio-economic metrics of the multidimensional impacts of agricultural innovation, some of which have not been well measured and understood – such as the effects on animal welfare, human health and nutrition, livelihoods, food security and food safety.

Apart from underfunding, policies tend to over-regulate some kinds of technologies (such as GMOs) and under-regulate others (such as pesticides) in certain production circumstances. What can be done to better communicate the economics of science and its consequences and to better understand the evolving public role in the funding and conduct of food and agricultural R&D, especially in the light of increasing and changing private roles?

A somewhat related, important question is the extent to which farmers (and others in the food and agricultural supply chain) benefit from research, and the distributional implications of agricultural innovations across different income or interest groups. Extant evidence on this question is entirely conditional on untested (or untestable) modelling assumptions – in particular assumptions about the nature of the research-induced technical change either explicitly or through the use of an industry 'technology'. In addition to *functional* income distribution, R&D has complex consequences for personal income distribution including direct and indirect effects on nutrition, health, life expectancy, quality of life and so on.

This distributional question relates to many others, including questions about the optimal design of institutions to enable appropriate mixtures of private individual, collective and public research funding, and execution of research programs. For example, we have only limited empirical understanding of the implications of the design of the RDC (Research and Development Corporation) system, or alternatives, for the total quantity of research expenditure, how that expenditure is funded, or the efficiency of allocation among alternative research investments. Similarly, a host of intellectual property and related matters about the design of public–private research relationships remain unresolved, for food and agricultural R&D in particular.

Other measurement questions go even deeper. Should we continue to work on measuring productivity, or would we do better to shift the focus back to a more complete accounting of the changing nature, sources (and consequences) of growth of agricultural output as Schultz (1956-S) proposed on the eve of the founding of AARES? What can be done to make output accounting or, equivalently, measures of productivity more inclusive – including often unpriced natural inputs and outputs provided from the environment and public goods such as infrastructure – and yet useful? How should we model and measure the returns to (policy-oriented) social science research, as well as research dealing with the nexus between the environment (including climate, pests, diseases and weeds) and agriculture, and other research in which the results are not embodied in some tangible technology, discrete institutional innovation or physical input? And how can we compare investments in such research with other investments with more easily quantifiable consequences to aid in resource allocation decisions?

This to-do list is long, albeit only partial, and the problems are difficult, and surely sufficient to keep many of us busy for the next 60 years.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1: Additional references called out in text with an 'S' designation.

Appendix S2: Australian Agricultural R&D: Individuals, Institutions, Policy and Practice

Appendix S3: Table S-1: Australasian Related Research Evaluation Evidence

Appendix S4: Table S-2: Australian Aggregate Agricultural Input, Output and Productivity Evidence