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# Public investment in R&D and extension and productivity in Australian broadacre agriculture

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## Abstract

This paper uses time-series data to examine the relationship between public research and development (R&D) and extension investment and productivity growth in Australian broadacre agriculture. The results show that public R&D investment has significantly promoted productivity growth in Australia's broadacre sector over the past five decades (1953 to 2007). Moreover, the relative contributions of domestic and foreign R&D have been roughly equal, accounting for an estimated 0.6 per cent and 0.63 per cent of annual total factor productivity (TFP) growth in the broadacre sector, respectively. The elasticity of TFP to knowledge stocks of research (both domestic and foreign) and extension were estimated to be around 0.20–0.24 and 0.07–0.15, respectively. The ranges reflect the alternative distributions of benefits flowing from knowledge stocks that were assumed in the analysis. The elasticities translated into internal rates of return (IRRs) of around 15.4–38.2 per cent and 32.6–57.1 per cent a year for research and extension, respectively. While such rates are less than the average IRR of around 100 per cent reported in the international literature, they are consistent with previous estimates for Australian agriculture in the order of 15–40 per cent.

**Key words: R&D, total factor productivity, agriculture**

# 1 Introduction

Increasing productivity in the agriculture sector continues to be an important policy objective of rural industries and Australian governments. Investment in research, development and extension (RD&E) is an important means of developing new technologies and management methods. In turn, facilitating industry adoption of such innovations serves to improve long-term agricultural productivity growth. In recent decades there has also been a focus on developing technologies that are both profitable for farmers and deliver better environmental and human health outcomes.

Notwithstanding the centrality of RD&E to productivity growth, there is an ongoing debate in Australia about the role that governments should play in funding agricultural RD&E and the returns to such public expenditure. These issues are especially relevant because agricultural productivity growth has slowed over the past decade or so, most notably in the cropping sector (Nossal and Sheng 2010). Extended poor seasonal conditions explain some of this slowdown, but a long-term decline in the growth of public RD&E since the 1970s has also been shown to be a factor (Sheng et al. 2010).

The returns to public agricultural R&D as reported in the literature appear significant, with no evidence that the rate of return to public RD&E investments is declining over time. Alston et al. (2010) surveyed a large number of studies and found that the median return to public investment in agricultural research was 48 per cent (the average being 100 per cent) across many different countries. Similar results have also been found in Australian studies that have focused on the broadacre sector. For example, Mullen and Cox (1995) estimated the internal rate of return (IRR) to publicly funded research in Australian broadacre agriculture (essentially, non-irrigated crops, beef cattle and sheep) to be in the order of 15–40 per cent between 1953 and 1988. Mullen (2007) also estimated similar rates of return for the period 1953–2003, suggesting high rates of return to public research have persisted in Australia.

However, the extent to which technology and knowledge 'spill-ins' from research conducted in other countries influences agricultural productivity growth in Australia is not well understood. Research conducted interstate or overseas can be a source of spillover productivity gains, whether as ideas gained from the research of others or through foreign technology adapted to suit local conditions. The small number of studies that have considered foreign spillovers have found that foreign R&D is as important—if not more so—as domestic R&D (Alston 2010). Moreover, foreign R&D is likely to be especially important for small, open economies such as Australia.

The objective in this paper is to re-examine the relationship between public agricultural RD&E investment in Australia and broadacre total factor productivity (TFP). The rate of return to public R&D was estimated using a research strategy similar to that used by Alston et al. (2010). A range of econometric techniques were applied to a dataset covering the period from 1953 to 2007. An important advance is to account for broadacre productivity gains arising from technology spill-ins from other countries and to distinguish between the relative contributions of foreign and domestic R&D and domestic extension activities to broadacre TFP growth. The results of several model specifications are presented, reflecting a range of assumed benefit distributions of public RD&E over time and, in turn, a range of internal rates of return. The limitations of the analysis and opportunities for further research into the relationship between agricultural productivity growth and investment in RD&E are also discussed.

# 2 Public RD&E investment and agricultural productivity in Australia

In Australia, the share of agricultural RD&E funded by the public sector has been much larger than that of the private sector—generally greater than 90 per cent of total agricultural R&D, although by 2007 this had decreased to 80 per cent (Mullen 2010). This contrasts strongly with other OECD countries where, on average, more than half of the total investment in agricultural research in 2000 came from the private sector. Not surprisingly, the extent of public investment in agricultural RD&E, and its effect on agricultural productivity, has consistently been an important policy issue in Australia.

Australian public investment in agricultural research has, in real terms, increased over the past 50 years, from A$140 million in 1953 (2008 dollars) to around A$829 million in 2007 (figure a). However, while growth in public R&D expenditure was strong until the late 1970s, it has since slowed. Research intensity (defined as the ratio of public RD&E expenditure to agricultural GDP) peaked at 5 per cent in 1978, before declining to 3 per cent in 2007. The annual growth rate of public R&D expenditure for agriculture has declined from around 7 per cent a year between 1953 and 1978 to around 0.6 per cent a year from 1978 to 2007.

## a Real public RD&E investment in Australian broadacre and US agriculture
### 1953–2007
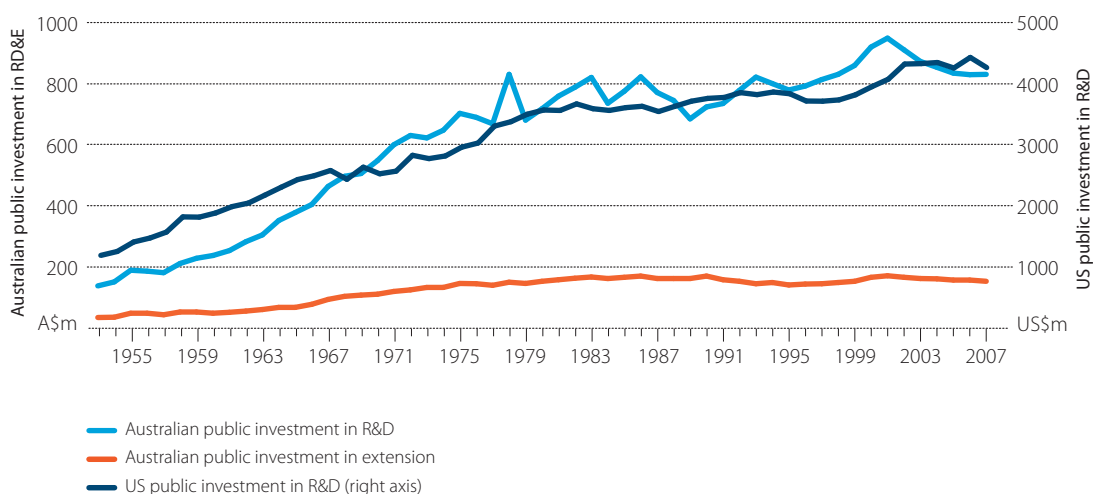


*Sources:* Estimated with data from Mullen 2010 and ERS-USDA.
*Notes:* In 2008 dollars. Australian public investment in R&D includes expenditure by state, territory and Commonwealth research institutions and universities, including funds from the research and development corporations and other external funders for agriculture, excluding research in fisheries and forestry.

A key objective of agricultural RD&E is to improve farm performance, particularly in relation to farm productivity. Generally speaking, TFP in broadacre agriculture in Australia has trended upward, from an index value of 100 in 1953 to 218 in 2007, peaking at 288 in 2000 (figure b). However, the slowdown in growth since the mid-1990s, particularly in the cropping industry, is concerning (figure c). Broadacre TFP growth averaged around 2.2 per cent a year before 1994 (a turning point year determined by Sheng et al. 2010), but declined to 0.4 per cent a year thereafter.

There is now evidence that stagnating public investment in RD&E since the late 1970s may have contributed to the slowdown in agricultural productivity growth (Sheng et al. 2010). Of course, there is a range of factors that could have contributed to the slowdown in broadacre TFP growth. Chief among these is drought, which has been a feature of agriculture for the past decade, particularly in 2003 and 2007. However, that stagnating public investment in RD&E should also be identified as a contributing factor is not surprising given the predominant underlying objective of such investment.

## b Broadacre TFP and terms of trade in Australia
1953–2007



Legend:
— terms of trade
— TFP
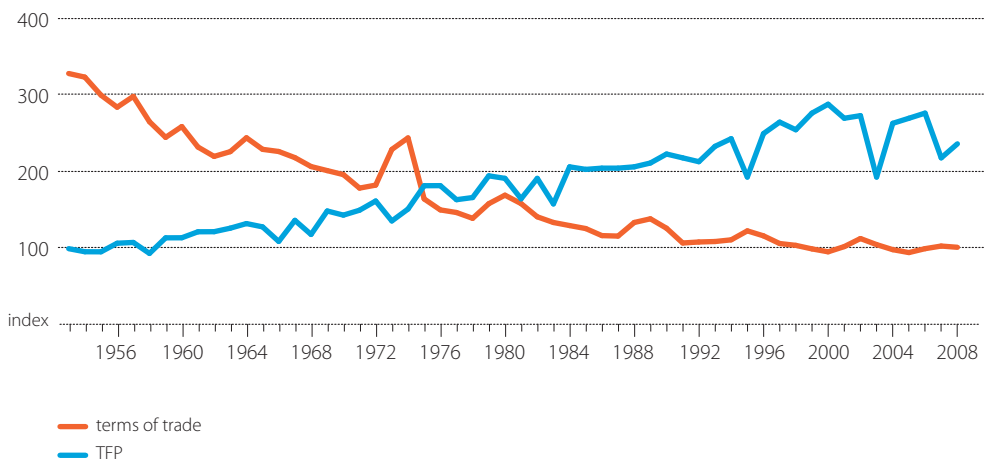
*Notes:* The terms of trade is the ratio of an index of prices received by farmers to an index of prices paid by farmers (ABARE 2009). TFP is the ratio of a quantity index of aggregate output to a quantity index of aggregate input (Gray et al. 2010).

# C TFP by broadacre farm type
1978–2008
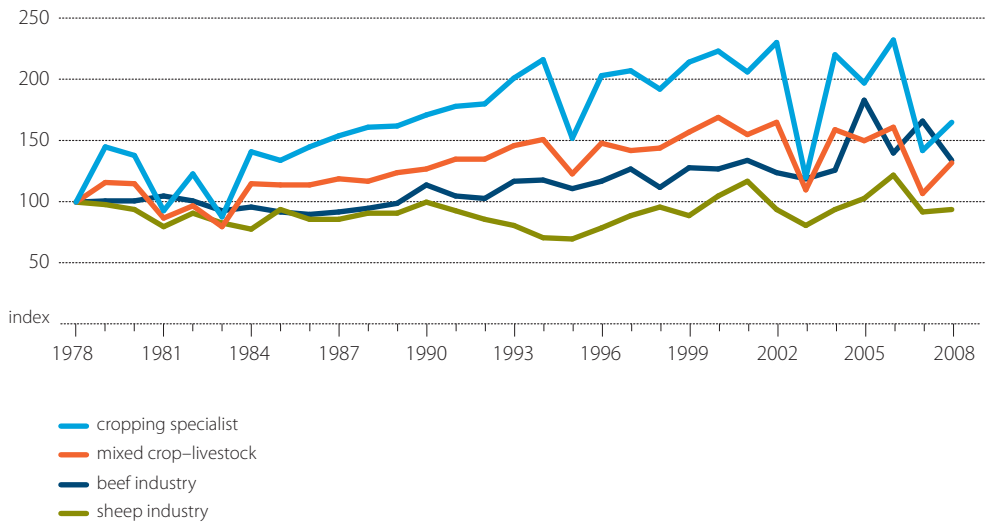


*Source:* Nossal and Sheng (2010).

# 2 Methodology and estimation strategy

For a variety of reasons, estimating a relationship between RD&E activities and agricultural TFP is complex. First, agricultural TFP in a given year does not depend on the current level of RD&E expenditures, but rather on the stock of usable knowledge derived from past RD&E expenditures (Alston and Pardey 2001). Second, there are usually long lags before investments can be converted into useful knowledge and technologies that are available for farmers to use (Alston et al. 2010). Thus, because it is unlikely that expenditure on R&D and, to a lesser extent, extension will be directly correlated with broadacre TFP in the same period, the unobserved knowledge stocks drawn on by farmers can be proxied by weighted aggregates of past expenditures on R&D and extension. In these matters, economic theory does not suggest an obvious estimation strategy, although past empirical studies do provide some guidance.

In the first instance, an unconstrained base model can be used to represent the relationship between RD&E knowledge stocks and TFP:

$$TFP_t = f(KS_t^{DS}, KS_t^{PS}, KS_t^{EXT}, KS_t^{FS}, Z_t) + \varepsilon_t \qquad (1)$$

where $TFP_t$ is the $TFP$ index at time $t$ and $KS_t^{DS}, KS_t^{PS}, KS_t^{EXT}$ and $KS_t^{FS}$ are knowledge stocks pertaining to expenditures on domestic public R&D, domestic private R&D, domestic extension and foreign public and private R&D, respectively. $Z_t$ is a vector of other control variables cited in previous studies (namely, seasonal conditions, the terms of trade and farmers' highest level of education attainment). A specific functional form is denoted by $f(.)$ and $\varepsilon_t$ is an error term.

A number of data limitations and various econometric issues mean it is not possible to directly estimate equation (1) without also encountering a range of statistical limitations. The balance of this section outlines a less direct, but more robust four-step estimation strategy involving:

- construction of the R&D and extension knowledge stocks
- choice of model specification
- choice of estimation strategy
- estimation of impacts and internal rates of return.

## Construction of knowledge stocks

The choice of the models for constructing the knowledge stock variables was based on the findings of previous international and domestic studies (Alston 2010; Alston et al. 2010; Mullen and Cox 1995) and econometric experimentation with similar models by the authors. A small group of models was selected that had sound statistical properties and economic implications, based on a series of econometric tests including the Ramsey RESET test and the root mean square error (RMSE) test. Knowledge stock variables were derived as the weighted average of past expenditure, using weights based on a suite of specific distributions (determined by an assumed duration and distribution shape of the impact of research over time):

$$KS_t^i = g_i(R_t^i, R_{t-1}^i, ..., R_{t-L_R^i}^i)$$

(2)

where $KS_t^i$ denotes the knowledge stocks corresponding to various RD&E activities
$i = \{DS, PS, EXT, FS\}$ as in equation (1). The investment at time $t$ is denoted by $R_t^i$ and the
maximum time lag for each knowledge stock variable is $L_R^i$. The distribution functions for
alternative time-lag profiles of R&D and extension are denoted by $g_i$ (.).

The time profile (that is, the duration and distribution of the lag profile) used to construct
knowledge stock variables was based on the likely features of the relationship between the
flow of research investments and the stock of usable knowledge. There are usually long but
uncertain lags between research investments and their eventual contributions to the stock of
useful knowledge. To reflect this, R&D lags of 16 and 35 years were considered in constructing
the R&D knowledge stock variables (following Mullen and Cox 1995). To describe the shape of
the lag profile, three distribution functions were considered: gamma, trapezoid and geometric
distributions. The geometric distribution was included because it reflects the perpetual
inventory method (PIM) approach that is commonly used to construct knowledge stocks for
the manufacturing sector (for example, Shanks and Zheng 2006). However, results obtained
with the geometric distribution are not discussed as the PIM approach is inconsistent with the
expectation that agricultural R&D investment will have little effect in its early years because of
long lags in adoption (Alston et al. 2010).

In total, knowledge stocks were constructed using 10 different distribution functions: three
gamma distributions (one with the peak impact occurring after seven years and two gamma
distributions that mimic the trapezoid (gamma_T) and geometric (gamma_P) distributions)
and the trapezoid and geometric distributions for both 16-year and 35-year lags.

In contrast to the relatively long R&D lag profiles, extension activities were expected to have
a much quicker, but still lagged, effect on productivity. The domestic extension knowledge
stock was assumed to follow a geometric distribution with a maximum lag length of four years
(Huffman and Evenson 2006).

## Choice of model specifications

To identify the relationship between the different types of knowledge stocks and TFP growth,
past approaches have usually needed to impose two constraints on the way in which the
model is specified. This is because of issues arising through multicollinearity (owing to the high
correlation between the knowledge stocks) and endogeneity (arising from excluding private
R&D).

First, following Mullen and Cox (1995), private R&D knowledge stocks were excluded from
equation (1). Time-series data on private R&D expenditure in Australian agriculture are not
generally available. Not including private R&D (domestic and foreign) may result in biased
estimates of the coefficients of public knowledge stock variables if private and public
knowledge stocks are correlated. For example, Alston and Pardey (2010) argued that, should
private R&D be positively correlated with public R&D, its omission would bias upward the
estimates of the coefficient on public R&D.

Although omitting private R&D knowledge stocks could potentially bias the results, there are reasons to believe that any effects may be less than would otherwise be expected. To the extent that farmers pay for the outputs of private sector research and services, the benefits of private R&D will be captured as an input in the TFP index. Conceptually, this would be the case if the private sector is able to appropriate some of the value of improved inputs, including consultancies to farmers. In other words, the productivity gains from an increase in output would be at least partially offset by the measured increase in higher quality inputs.

Furthermore, in the case of Australia, the private share of agricultural R&D has been small relative to public investment, exceeding 10 per cent only in recent years. Given the long lags between research investments and their eventual contributions to the stock of knowledge, it is likely that domestic private R&D has had a relatively limited effect on broadacre TFP to date. However, excluding foreign private R&D remains a possible source of bias of unknown importance and an area for future research.

Second, rather than estimate the individual effects of domestic and foreign public knowledge stocks (equation 1), it was necessary to form a total public research knowledge stock variable ($TS_t^{kj}$) to deal with the high correlation between foreign and domestic public R&D knowledge stocks. Foreign (public and private) R&D is expected to contribute directly to TFP growth in Australia through cross-country technology spillovers. Not controlling for the impact of foreign public knowledge stocks may also result in omitted variable bias, leading to overestimates or underestimates of the contribution of domestic public R&D and extension knowledge stocks to productivity.

Two assumptions guided construction of the total public R&D knowledge stock variable. First, domestic and foreign public R&D were assumed to have the same lag profiles. Second, the foreign public R&D knowledge stock was assumed to have a smaller effect on broadacre TFP than the domestic public R&D knowledge stock. This was to take into account possible differences in agricultural production techniques, the focus of public R&D investment and possible trade and non-trade barriers to agricultural knowledge transfers across countries. It is likely that spillover productivity gains from external R&D are greater when the technology or knowledge is sourced from regions (or countries) that have similar agroecological conditions, as less investment in adaptive research is required (Sunding and Zilberman 2001). Similarly, openness to trade and investment increases the transfer of knowledge and technology between countries and, in effect, facilitates access to the outputs of foreign R&D. In contrast, the jurisdictional pattern of intellectual property rights may act as a non-trade barrier to international technology flows (Alston 2010).

The total public research knowledge stock variable ($TS_t^{kj}$) was constructed as a weighted sum of domestic and foreign public R&D knowledge stocks. Correlation between domestic and foreign public R&D knowledge stocks made it necessary to aggregate these variables to form a single public research knowledge stock variable. The approach for selecting a value for the weight on foreign public R&D knowledge stocks ($\pi$) was similar to that used by Alston et al. (2010), which was based on the degree of similarity in production patterns in the United States and Australia. Consistent with Shanks and Zheng (2006), Australia's openness to trade was also taken into account. The value of foreign spill-ins ($\pi$) was set to 0.1. This yielded the total public research knowledge stock variable, $TS_t^{kj}$, such that $TS_t^{kj} = 1\text{n } KS_t^{DS} = + 0.11\text{n } KS_t^{FS}$.

Although not feasible for this study, it is likely that further research into a more formal derivation of the value of , the weight on spill-ins from foreign public R&D knowledge stocks, would be useful. In this analysis, the value of $\pi$ was heavily influenced by the performance of the weighting factor in the Ramsey RESET and CUSUM specification tests, rather than how easily knowledge and technology are transferred across countries in practice.

## Regression method and estimation strategy

Given the methodology, the base model for examining the relationship between public research and extension knowledge stocks and broadacre TFP became:

$$\ln(TFP_t) = \alpha + \beta_1 \ln(TS_t^{kj}) + \beta_2 \ln(EXT_t) + \gamma_1 \ln(WEA_t) + \gamma_2 \ln(EDUC_t) + \gamma_3 \ln(TOT_t) + \varepsilon_t$$

(3)

where the superscripts $k$ and $j$ denote the lag duration (length) and distribution (shape) of the research benefit profiles.

Following Mullen and Cox (1995), equation (3) also included three control variables that could affect productivity, but which are not reflected specifically in the TFP index: a measure of seasonal conditions (essentially, water availability) ($WEA_t$); farmers' education attainment as a proxy for the unobserved human capital of broadacre farmers ($EDUC_t$); and the farmers' terms of trade for Australian agriculture at time $t$ ($TOT_t$). The rationales for including each control variable are:

- Water availability can substantially depress TFP estimates in drought years because the broadacre industries (grain, beef and sheep production) are predominately dryland (non-irrigated) enterprises.

- Human capital formation is a driver of agricultural productivity growth, which may be proxied by the education level of farmers. If labour can be differentiated in the TFP index according to education and weighted by prices that are indicative of labour quality, then improvements in human capital are effectively embodied in the labour input and will not be reflected in TFP estimates. However, ABARES only differentiates labour according to whether it is hired labour, services provided by shearers, or owner-operator and family members. Therefore, the effect of human capital formation on agricultural productivity will not be captured by the TFP index, but will be reflected in TFP estimates.

- Changes in the terms of trade may, in the short run, induce farmers when profit-maximising to choose combinations of inputs and outputs that reduce their overall productivity (O'Donnell 2010; Productivity Commission 2008). For example, farmers may expand cropping into relatively marginal land in response to increases in expected output prices.

There are other factors that could influence agricultural productivity which are not included in equation (3). For example, the agriculture sector has experienced spillover productivity gains from government investment in transportation and communication infrastructure. Changes in the structure of the farm sector are also likely to be sources of productivity growth. However, it can be difficult to identify suitable proxies for these variables and, to the extent that these variables are not correlated with the independent variables in equation (3), excluding them from the analysis should not introduce bias in the time-series regression model.

A time-series regression technique—the autoregressive integrated moving average (ARIMA) model, which assumes the residuals ($\varepsilon_t$) follow a random normal distribution—was used to estimate equation (3). Although the model can be estimated using ordinary least squares (OLS), such estimates may be biased and inefficient because OLS fails to take into account the time-series properties of the data. For example, if $1\text{n}(TFP_t)$ and $1\text{n}(TS_t^{kj})$ are positively correlated with time (that is, they have time-trend unit roots), then OLS may estimate a spurious relationship between them (Greene 2007).

# 3   Data sources and variable definitions

The measure of productivity used in the regression analyses is the ABARES broadacre TFP index, which is defined as the ratio of a Fisher quantity index of total output to a Fisher quantity index of total input. An exposition of the concepts, theories and empirical methods underlying the ABARES TFP estimates for the broadacre (and dairy) industries can be found in Gray et al. (2010). All related data were collected through the ABARES broadacre farm surveys, which cover the period from 1953 to 2007, and were aggregated to the national level.

Domestic public R&D investment was defined by total public R&D expenditure on plants and animals and excludes fish and forestry R&D. Data were obtained from two sources:

- Raw data for 1995–2007 were sourced from the Australian Bureau of Statistics (ABS) biannual Australian Research and Innovation Survey (ABS 2008).
- Data before 1994 were drawn from Mullen et al. (1996), who sourced data from the Commonwealth Department of Science and the published financial statements of the state departments of agriculture and their counterparts.

The absence of a sufficiently long time series on R&D and extension investments also presents a challenge. Given previously identified research lags of 35 years, public R&D expenditure data are needed as far back as 1918. To address this problem, a procedure described in Mullen and Cox (1995) was used to 'backcast' the series. Public R&D expenditure data for the period 1918 to 1953 was extrapolated backwards using actual R&D data from 1953 to 1980.

Investment in extension was derived from state departments' total public RD&E expenditure records. Because a breakdown of total expenditure into research and extension is generally unavailable, extension expenditure was estimated using past department surveys of time spent by staff on functions such as research, extension and regulation. The share of extension in total research expenditure for the period from 1953 to 1994 ranged from 27.4 per cent (in 1965) to 39 per cent (in 1958), with no apparent trend. As for public R&D investment, data on investment in extension before 1953 were backcast, with the proportion of public investment in research extension assumed to be one-third of the state departments' total investment in research.

The use of backcast R&D and extension investments before 1953 allows the full broadacre TFP series from 1953 to 2007 to be used to estimate equation (3), and likely reduces the possibility of an upward bias to the estimated rates of return arising from specifying insufficiently long research lags. The backcasting procedures used to extend the series do not create any new information (Mullen and Cox 1995), and the created data were used only in the construction of the R&D and extension knowledge stocks variable.

R&D investment in the broadacre agriculture sector was derived by applying broadacre agriculture's share of the total value of production in agriculture to total public investment

in agricultural R&D. The GDP deflator was used to derive real public R&D and extension expenditure.

Foreign public R&D expenditure was proxied by US public R&D expenditure on agricultural production related research. The United States has had a pivotal role in global agricultural R&D, not only in terms of its investment compared with the rest of the world, but also in terms of 'know-how' and new technology spillovers arising from research conducted in the United States. The raw data for the period from 1970 to 2007 were obtained from the Economic Research Service of the US Department of Agriculture. The pre-1970 data were aggregated state-level data from Huffman and Evenson (2006).

Seasonal conditions ($WEA_t$) were approximated by an index of moisture availability for broadcre agriculture. Moisture availability—more precisely, the annual wheat water stress index (Potgieter et al. 2002)—is a measure of the relative water stress of the crop accumulated throughout the growing season. The index was simulated using daily rainfall and average weekly radiation data, maximum and minimum temperatures, location-specific soil data and crop-specific water requirements. The index reflects the cumulative stress endured by the crop throughout the season relative to its initial value of 100 at the start of the season. In the absence of a consistent seasonal conditions dataset from which to estimate the moisture availability index, an index was constructed from different datasets over time. These included the annual wheat water stress index at the national level (1953–1988), a weighted average of the annual wheat water stress index at the farm level (1989–2004), and a weighted average of farm-level total rainfall (2004–2007).

Broadcre farmers' education attainment ($EDUC_t$) was proxied by the proportion of school-age students in the total population enrolled in schools, using ABS data (Mullen and Cox 1995). Enrolment was defined as 'school attendance' or 'the number of school students at the national level'. The education index used here is a crude proxy for the real variable of interest, the human capital stock of broadcre farmers. Since farmers' education attainment is likely to differ from that of the total population, future research into the relationship between agricultural productivity growth and investment in RD&E would possibly benefit from development of a more appropriate measure (such as education levels of the rural population) for the human capital stock of farmers.

The farmers' terms of trade ($TOT_t$) is the ratio of the average price received by farmers for their output to the average price paid for farm inputs. It covers all agriculture (not just broadcre) and was derived from data in *Australian commodity statistics* (ABARE 2010).

# 4 Estimation results: effects of R&D on productivity

A range of model specifications for equation (3) were investigated to identify a preferred model and to establish the robustness of the main results. These investigations produced a large set of results that cannot be usefully summarised here. However, the statistical tests suggested that:

- a 35-year lag period for capturing the effects of past R&D expenditure was preferable to a 16-year period (the models with 16-year lags did not pass the RMSE specification test and are not discussed further)
- the log-linear function form for equation (3) was preferable to linear and quadratic functional forms
- aggregating domestic and foreign R&D to construct a total public research knowledge stock variable was preferred to the past practice of omitting foreign R&D (as in Mullen and Cox 1995).

In addition, a standard gamma distribution with peak impact occurring after seven years was preferred over alternative distributions (gamma_T, gamma _P, trapezoid and PIM).

## Effects of R&D and extension knowledge stocks on agricultural TFP

The estimated elasticity of TFP with respect to public R&D knowledge stocks was positive and significant for all distribution profiles (table 1). In the preferred gamma specification, the coefficient on public R&D knowledge stocks was 0.23, implying that a 1 per cent increase in the public R&D knowledge stock is likely to lead to a 0.23 per cent increase in broadacre productivity.

Similarly, the results suggest that increases in public extension knowledge stocks have had a significant and positive effect on productivity, with an elasticity of around 0.1 per cent. The marginal impact of the extension knowledge stock on TFP was, on average, around half that of the public R&D knowledge stock, where R&D and extension knowledge stocks both increased at the same rate.

The relative contributions of public R&D and extension knowledge stocks to annual TFP growth between 1953 and 2007 can be calculated by multiplying the elasticities (from table 1) by the annual growth rates of the corresponding knowledge stocks. The elasticity of TFP to foreign public R&D knowledge stocks is the coefficient on total public R&D knowledge stocks deflated by $\pi$, which is the weight for foreign public R&D knowledge stocks used to construct the total public R&D knowledge stock variable.

# 1    Elasticities of TFP to public RD&E knowledge stocks and other explanatory factors

| | Gamma | Gamma_T | Trapezoid | Gamma_P | PIM |
|---|---|---|---|---|---|
| Dependent variable: ln(TFP) | | | | | |
| Public R&D knowledge stock (log) | 0.23*** | 0.23*** | 0.20*** | 0.24*** | 0.20*** |
| | (0.05) | (0.05) | (0.05) | (0.06) | (0.05) |
| Extension knowledge stock (log) | 0.10*** | 0.10*** | 0.14*** | 0.07** | 0.15*** |
| | (0.04) | (0.03) | (0.03) | (0.04) | (0.03) |
| Water stress indicator (log) | 0.28*** | 0.27*** | 0.28*** | 0.26*** | 0.28*** |
| | (0.05) | (0.06) | (0.06) | (0.06) | (0.06) |
| Education (log) | 0.56 | 0.66* | 0.02 | 0.85** | 0.29 |
| | (0.37) | (0.38) | (0.40) | (0.39) | (0.39) |
| Terms of trade (log) | −0.27*** | −0.24** | −0.26*** | −0.26*** | −0.26*** |
| | (0.08) | (0.10) | (0.08) | (0.10) | (0.09) |
| Constant | −0.33 | −0.85 | 1.84 | −1.37 | 0.61 |
| | (1.69) | (1.82) | (1.57) | (1.91) | (1.65) |
| Number of observations | 55 | 55 | 55 | 55 | 55 |

*Notes:* \*\*\*, \*\* and \* represent statistical significance at 1 per cent, 5 per cent and 10 per cent levels, respectively. ARIMA model with 35-year lag. The values in parentheses are standard errors. 'Gamma' refers to the preferred model specification in which a standard gamma distribution was used to construct knowledge stocks, with a peak impact occurring seven years after investment.

Growth in public R&D and extension knowledge stocks has accounted for more than half of annual TFP growth in the broadacre sector between 1953 and 2007. Broadacre TFP growth averaged around 1.96 per cent a year between 1953 and 2007. Over this period, public R&D knowledge stocks increased by an average 5.8 per cent a year, accounting for approximately half of annual broadacre TFP growth a year (around 0.96 per cent). This comprised 0.33 per cent a year from the accumulation of domestic public R&D knowledge stocks and 0.63 per cent a year from the accumulation of foreign public R&D knowledge stocks. Growth in public extension knowledge stocks, which increased by an average 3.2 per cent a year, contributed around 0.27 per cent to TFP growth a year. This suggests that, between 1953 and 2007, the relative contribution to broadacre TFP growth of domestic and foreign research activities and domestic extension activities was in the ratio of 1:2:1.

Of the three control variables, seasonal conditions and the farmers' terms of trade had significant effects on broadacre TFP. The estimated elasticities of TFP with respect to seasonal conditions ranged from 0.26 to 0.28 for all distributions, indicating that a 1 per cent increase in moisture availability over the growing season would be expected to increase productivity in that year by 0.28 per cent, all other things being constant.

In contrast, the farmers' terms of trade had a negative effect on broadacre TFP. The elasticity of TFP with respect to the terms of trade was −0.27 in the preferred gamma distribution (ranging from −0.24 to −0.27), indicating that a 1 per cent improvement in farmers' terms of trade would, on average, lead to a 0.27 per cent fall in productivity, all other things being constant. As indicated earlier, a possible explanation is that improvements in the terms of trade may induce farmers when profit-maximising to choose combinations of inputs and outputs that, in the short term, reduce their overall productivity.

The elasticity of TFP with respect to the level of education attainment was positive but insignificant. To some extent this is unexpected since human capital can facilitate technology adoption and improve farmers' ability to organise and maintain complex production processes. As suggested earlier, the national education attainment index used in the analysis may not be a good proxy for the human capital stock of broadacre farmers.

## Return to public investment in RD&E: a cost–benefit analysis

The above analysis provides evidence of the positive impact of R&D and extension knowledge stocks on TFP in the Australian broadacre sector. However, of further interest from a policy perspective is the return from public R&D and extension. The internal rates of return (IRRs) to public investment were calculated using the elasticities of TFP to the R&D and extension knowledge stocks. Estimates of the IRR to public investment provide a measure of the benefits from a one-off increase in public expenditure on agricultural R&D and extension, which can be used ex post as a measure of the returns achieved and ex ante to assist in resource allocation.

Over the period from 1953 to 2007, the IRR to public investment in agricultural R&D was 28.4 per cent a year in the preferred model, and ranged from 15.4 to 38.2 per cent in the other specifications (table 2). The differences in IRRs across the distributions arose from the different weights assigned to the lagged years, since the estimated elasticities are quite similar in magnitude. Generally, distributions that assigned greater weights to more recent years generated higher IRRs.

## 2   IRR from domestic public investment in agricultural R&D and extension activities (%)

| | Gamma | Gamma_T | Trapezoid | Gamma_P | PIM |
|---|---|---|---|---|---|
| Public R&D | 28.4 | 14 | 15.4 | 38.2 | 51.9 |
| Extension | 47.5 | 35 | 32.6 | 57.1 | 79.5 |

Public extension generated significantly higher IRRs than those for public R&D. Over the period from 1953 to 2007, the IRR estimated from the preferred gamma specification for public extension was 47.5 per cent, but ranged from 32.6 per cent to 57.1 per cent. The higher rates of return to extension than R&D may be because of the relatively quicker (although still lagged) effect on productivity of extension activities (Huffman and Evenson 2006). In addition, public extension may facilitate adoption of spill-in technology from foreign public R&D investment. However, the IRRs should be viewed with caution, given the source and approach taken in constructing the extension dataset (as outlined previously). Despite these qualifications, the estimated IRRs for R&D and extension were relatively consistent with the median rates of return in the international literature reported in Alston et al. (2010).

To determine if the IRR to public R&D has changed over time, the estimation procedure was repeated for the period 1978 to 2007. Growth in public R&D expenditure has slowed since the late 1970s, with research intensity peaking at 5 per cent in 1978 before declining to 3 per cent in 2007.

The estimated IRR from public agricultural R&D over the period from 1978 to 2007 was 45 per cent in the preferred model (table 3). This is significantly higher than the IRR estimated for the period from 1953 to 2007. Since the procedure used to estimate IRRs for the period from 1978 to 2007 is the same as that described earlier, the larger IRRs in the more recent period were a result of an increase in the elasticity of TFP to public R&D knowledge stocks (from 0.20–0.23 to 0.31–0.45). Compared with the IRR estimated for the period from 1953 to 2007, these results suggest that the returns to public agricultural R&D may be increasing, possibly because growth in public R&D has been falling since the 1970s.

# 3   Comparison of return to domestic public R&D investment in agricultural R&D

|  | Gamma | Gamma_T | Trapezoid | Gamma_P | PIM |
|---|---|---|---|---|---|
| Elasticity |  |  |  |  |  |
| 1978–2007 | 0.45 | 0.35 | 0.41 | 0.31 | 0.34 |
| 1953–2007 | 0.23 | 0.23 | 0.20 | 0.24 | 0.20 |
| IRR (%) |  |  |  |  |  |
| 1978–2007 | 45.3 | 21.0 | 24.1 | 69.2 | 81.0 |
| 1953–2007 | 28.4 | 14.0 | 15.4 | 38.2 | 51.9 |

In contrast, the estimated elasticities of TFP to the public extension knowledge stocks were not significant (even at the 10 per cent level) for all distribution scenarios over the period from 1978 to 2007, possibly because of the limited time series. Consequently, an IRR could not be estimated for public investment in extension over the period from 1978 to 2007.

# 5 Conclusions

Public and private sector investment in agricultural RD&E has been an important source of agricultural innovations, enabling productivity growth in the Australian broadacre sector. In this paper, the relationship between public agricultural RD&E investment in Australia and broadacre TFP over the period 1953 to 2007 was re-examined, taking into account technology spill-ins from overseas research.

Public investment in broadacre R&D and extension has generated rates of return that could be as high as 28 per cent and 47 per cent a year, respectively. While little is known about the opportunity cost of public investment in RD&E, this rate of return is comparable to rates of return estimated for other developed countries (Alston et al. 2010). Further, the growth in domestic public R&D and extension knowledge stocks arising from this investment has accounted for 0.33 per cent and 0.27 per cent, respectively, of TFP growth annually in the broadacre sector (an aggregate of 0.6 per cent).

An important aspect of this analysis was to seek to identify the contribution of foreign R&D relative to domestic public RD&E to broadacre productivity growth. Growth in foreign public R&D knowledge stocks has accounted for an estimated 0.63 per cent TFP growth annually in the broadacre sector. Although further research may be useful to refine these estimates, the results suggest the relative contributions of foreign and domestic research activities (including domestic extension) to broadacre TFP growth have been roughly equal.

As indicated in the discussion of the model specification, data and resulting estimates, this analysis has a number of limitations that further research might usefully address. The limitations arise in part from data constraints, including the unavailability of domestic and foreign private research expenditures; data on R&D investments before 1953; and the lack of a more appropriate proxy for the human capital of broadacre farmers.

This analysis has focused on quantifying the private returns to public investment in RD&E activities. However, a range of social benefits from publicly funded research may arise through the application of rural R&D outputs beyond the broadacre sector and/or incidental effects on environmental quality or human health and safety. To the extent that public investment in agricultural RD&E activities benefit society more broadly (that is, beyond broadacre farmers), accounting for such social benefits would translate into higher internal rates of return to public investments in agricultural RD&E than those estimated in this paper.

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