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The Yield of Plant Variety Protection*

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Abstract

This article examines the effect of the introduction of plant variety protection on the output of Australian wheat breeders. The Australian experience has global relevance due to the relative strength of plant variety protection introduced in 1994. The analysis uses extensive new data on the performance of all 250 varieties released between 1976 and 2011. A comprehensive framework for measuring breeder output using data from scientific variety trials is developed. The results indicate that plant variety protection led to a 24 percent reduction in annual breeder output. The results support the conclusion that plant variety protection alone does not generate the socially optimal rate of variety improvement in the case of self-pollinating crops, and therefore, that additional government support is warranted.

JEL classifications: O34, Q16, Q18.

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Over the past century new and improved seed varieties have increased yields of cereal crops by an average of one percent per annum; about half of total yield gains (Duvick 2004; Fischer and Edmeades 2010). Historically, the role of the private sector in breeding new varieties of self-pollinating staples such as wheat and rice has been limited. It is difficult for private breeders to generate a commercial return on breeding these varieties because they can be grown from saved seed.[1] This situation is changing owing to the increasing adoption of plant variety protection, which is now in place in at least 70 countries (UPOV 2013). Plant variety protection is a relatively recent form of intellectual property rights which aim to give breeders the ability to collect royalties from growers who cultivate protected varieties. The purpose of plant variety protection is to encourage private investment in breeding and to furnish breeders with an incentive to develop efficient breeding practices and to target attributes most valued by growers. However, despite global enthusiasm for plant variety protection, systematic evidence of its effectiveness has proved elusive.

There is little doubt that private investment in breeding self-pollinated varieties is contingent on plant variety protection. What is less clear is whether plant variety protection alone can generate a socially optimal supply of new varieties. It is well known that intellectual property rights do not provide an optimal incentive to innovate in all cases – particularly where innovations are cumulative and sequential, as crop improvement tends to be (see e.g., Gallini and Scotchmer 2002). Intellectual property rights can also potentially reduce breeder productivity, for example, by impeding knowledge sharing (Kingwell 2005; Byerlee and Dubin 2010; Czarnetzki, Gimpe and Toole 2013). However, plant variety protection supports breeding by private firms which can outperform public organisations under some conditions (see e.g., Hart, Shleifer and

Vishny 1996). Ultimately, empirical evidence is needed to evaluate the overall impact of plant variety protection.

This article presents new evidence on this issue by analysing the effect of plant variety protection, introduced in 1994, on the Australian wheat breeding sector. Existing research has focused almost exclusively on the North American experience, where plant variety protection provides for limited appropriation of rents by breeders of self-pollinating varieties (Alston and Venner 2002; Gray and Boleck 2012). By most measures, plant variety protection in Australia is 'stronger' than the system in either the U.S. or Canada. Importantly, in Australia royalties are payable on all farm output produced using a registered variety, including on crops grown from saved seed. Unlike the situation in North America, the Australian system has underpinned complete withdrawal of all direct government funding of wheat breeding. Alston, Gray and Bolek (2012 p.63) suggest that "North America, well behind Australia, has the advantage of being able to learn from Australia's successes."

There is no established method for evaluating the impact of plant variety protection on breeder output. Some researchers have examined whether registered varieties are higher yielding than those that are not registered (e.g., Carew and Devado 2003; Alston and Venner 2002; Naseem, Oehmke, and Schimmelpfenning 2005; Carew and Smith 2006; Carew, Smith and Grand 2009). Their findings – which have been mixed – are hard to interpret because we do not know why breeders choose to register some varieties and not register others. Other research suggests that privately bred varieties in the U.S., which constitute a minority, are higher yielding than public varieties (Kolady and Lesser 2009). However, it is problematic to attribute this solely to the relatively weak U.S. system of plant variety protection, since private and public breeders do not necessarily target the same seed markets. Finally, some researchers have compared either the level of investment, or the performance of varieties released, before and after policy reform – though none have established a significant effect (Kalton *et al.* 1989; Babcock and Foster 1991; Frey 1996; Alston and Venner 2002; Moser and Rhodes 2011).

This article sets out a comprehensive method for modelling the effect of plant variety protection on breeder output using data from scientific crop variety trials. Output is defined as the extent to which varieties released by each breeder cumulatively expand the potential productivity frontier of Australian wheat farms. The analysis focuses solely on the creation of new varieties and does not directly consider whether or not the varieties are adopted by farmers. As will be outlined, this caveat does not preclude some important normative conclusions being drawn. The approach accommodates the fact that varieties which perform below the incumbent do not expand the frontier. Additionally, rather than measuring performance using yield alone, a more nuanced index is developed which incorporates yield, end-use quality and disease resistance. This is important because breeders face trade-offs between yield and other attributes and these trade-offs are likely to be influenced by the introduction of plant variety protection.

The results indicate that the introduction of plant variety protection and the ensuing shift to royalty-funded breeding led to a 24 percent reduction in breeder output. This finding suggests that strong plant variety protection alone does not ensure socially optimal breeding outcomes in the case of open-pollinated varieties. While strong plant variety protection may be beneficial, additional government support for breeding appears warranted.

A natural experiment

The Australian wheat breeding sector provides a veritable ‘pilot study’ for assessing the prospects for strong plant variety protection to deliver improved varieties of self-pollinating crops. This has relevance to the major grain markets of North America and to the developing world, both of which depend predominantly on publically and multilateral funded breeding programs (in self-pollinating crops). Australia is also a substantial contributor to global wheat markets, producing around 12 percent of total world exports (Productivity Commission 2010).

For over a century Australian wheat breeding was undertaken almost exclusively by government.[2] New varieties were distributed freely by a network of approved growers supported by government agronomists. The economic rationale for government breeding is that a wheat variety is a public good, since it is non-rival and it is difficult to exclude farmers from growing it (in the absence of effective intellectual property protection). Of all crop types, wheat epitomises non-excludability, since virtually all wheat varieties grown commercially are self-pollinating. This means a small sample of a new variety can be multiplied (‘bulked up’) in a short time at almost negligible cost. Unlike wheat, most cultivated varieties of corn, canola and soybeans are hybrids. Hybrid varieties provide for considerably stronger appropriation conditions because farmers generally buy new hybrid seed every year, since saved seed does not perform as well as the original.[3] It is almost certainly no coincidence that private breeders in North America have been heavily active in corn, canola and soya breeding but largely eschew wheat breeding (Malla and Gray 2000; Bolek and Gray 2012).

The Australian *Plant Breeders Rights Act* (The Act) became law in 1994. The Act was required for Australia to meet its obligations under the *International Convention for the*

Protection of New Varieties of Plants and was also consistent with the policy objective of reducing public investment in breeding (Kingwell 2005; Gray and Boleck 2012).[4] The Act enables breeders to collect royalties on total wheat production – including crops grown from saved seed. Royalties are collected where grain is delivered to a silo, so 'leakage' is only possible when grain is consumed on farm. This system is known as 'end-point royalties'. The relative strength of the system makes this episode of intellectual property reform a particularly appealing example to study. The first variety to attract an end-point royalty, *Goldmark*, was released in 1996. Subsequently the industry went through a transition period as an increasing share of new varieties attracted end-point royalties. Some breeders shifted to the royalty funded model more rapidly than others.

By enabling the collection of end-point royalties, plant variety protection facilitated privatisation of the Australian wheat breeding sector. Immediately prior to the introduction of the Act, the sector consisted of seven public breeding programs (a complete list of breeding programs is provided in the appendix). Historically these were funded through a mixture of state and federal government funding, and new varieties were distributed freely to farmers. From 1989 growers also contributed to breeding through a flat per-tonne levy, which is not tied to the specific variety cultivated. Between 1995 and 2007 each of the state government breeding programs were acquired by one of two new private companies: *Australian Grains Technology* and *Intergrain*, both of which operate on a self-funding 'for-profit' basis. New private breeders have also entered the market, most notably *Longreach*. The introduction of end-point royalties enabled breeders to shift to royalty-based funding. Government funding was phased out gradually after the end-point royalty system was established, and in 2005 the GRDC ceased all direct funding to breeders.

There are two mechanisms through which the introduction of plant variety protection may have affected breeder output: by changing total investment, or by changing breeder productivity. Total investment may have changed given that it is not known whether induced private investment matched the amount of public funding withdrawn over the period. The predicted effects of the reforms on productivity are also ambiguous. On one hand, private firms outperform public organisations under some conditions (see e.g., Hart, Shleifer and Vishny 1996). On the other hand, competition for monopoly rents may reduce collaboration or exchange between breeders (Kingwell 2005, Byerlee and Dubin 2010). Moreover, since private breeders specialize in applied breeding, leaving 'basic' research to government research agencies and universities, the reforms potentially introduce 'technology transfer problems' and inhibit the timely flow of information from basic scientific researchers to applied breeders (see e.g., Bozeman 2000). Under some conditions breeders may also be reluctant to release new varieties which cannibalize their own monopoly rents (see e.g., Tirole 1988 p.399; Scotchmer 2006). This article does not aim to identify the mechanism through which plant variety protection has affected breeder output, if at all. However, as is outlined below, understanding the mechanism is not requisite to assessing whether the introduction of plant variety protection in Australia was welfare improving or not.

Two conditions must be met for the introduction of plant variety protection to improve welfare. First, the rate of improvement in the varieties actually *sown by farmers* must be higher after the reform. Second, the total value of additional farm output achieved by sowing the new varieties must be greater than the additional resources invested in breeding. Breeder output must increase for the first condition to be met because plant variety protection cannot increase the rate of adoption of new varieties (though it may decrease it). Recall that before plant variety protection, new varieties were actively distributed at no financial cost to farmers. Regarding the second condition, estimates of the social rate of return to breeding indicate that breeder output was below the social optimum prior to the reform – that is, the social rate of return was substantially higher than typical measures of the social discount rate (e.g., Brennan, Martin and Mullen 2005).[5] Increased breeder output can therefore be viewed as a necessary but not sufficient condition for plant variety protection to provide a welfare gain.

Analytical Framework

This article aims to quantify the effect of plant variety protection on breeder output. Breeder output is defined as the cumulative contribution of the varieties released to the potential productivity frontier of Australian wheat farms. Under the proposed framework, a breeder's output reflects the entirety of their contribution to the national potential productivity frontier; it does not reflect only the performance of their best varieties, nor solely their performance in the selected seed markets in which they chose to operate. The analytical framework for measuring the value of breeder output is outlined below.

Let π_i denote the 'profit' per hectare that a farmer can generate by cultivating variety *i*. Profit is defined as the market revenue, which is the quantity of grain harvested multiplied by its price per tonne, less farming input costs. The price per tonne of harvested grain is determined by its value to consumers, which in turn reflects the quality of breads, pastries and noodles that can be produced from flour milled from the grain; this is called the variety's 'end-use quality'.

The profit maximising variety (which will be referred to as the incumbent) defines the production possibility frontier which will be denoted by $\pi_{\text{incumbent}} = \underset{i}{Max}\left(\pi_i\right)$.[6] Note that the frontier is determined by the set of all varieties available at any time and therefore evolves as new varieties are released.

The potential additional profit per hectare (which will be denoted by Δ_i) that can generated by sowing new variety *i* instead of the incumbent is given by:

$$\Delta_i = \pi_i - \pi_{\text{incumbent}} \tag{1}$$

Note that all farming costs which are invariant to the choice of variety are differenced out in equation 1 (since they are incurred regardless of whether variety *i* or the incumbent is cultivated). Note that the potential additional value-added per hectare is equivalent to the potential additional profit per hectare (i.e., Δ_i, as defined in equation 1) assuming that the choice of variety does not affect labour or machinery costs.

Depending on whether or not variety *i* performs better than the incumbent, the potential additional profit (Δ_i) can be either positive or negative. A variety only expands the production possibility frontier if cultivating it generates *positive* additional profit. If a variety generates a negative additional profit, it contributes zero to the production possibility frontier. Therefore the contribution of variety *i* to the production possibility frontier (for given, fixed farm inputs) is given by:

$$\Delta_i^+ = \begin{cases} \Delta_i & \text{if } \Delta_i > 0 \\ 0 & \text{if } \Delta_i \leq 0 \end{cases} \tag{2}$$

In practice, the land devoted to cultivating wheat is heterogeneous in terms of agro-ecological attributes, such as average rainfall and soil type. The performance of each variety (e.g., yield and end-use quality) varies between different locations because it reflects the interaction of genetics (specific to the variety) and environmental factors (specific to each location). To accommodate the fact that the performance of each variety differs across space, assume that the total area of land on which wheat is cultivated is divided into M distinct agro-ecological environments, henceforth referred to as regions. Both the rank order and magnitude of profit achievable by growing each variety can be different in each region.

The contribution of new variety *i* to the *aggregate* national production possibility frontier, in terms of dollars per hectare, is equal to the area-weighted sum of variety *i*'s contribution to the frontier in each region. Let Q_i denote the contribution of variety *i* to the aggregate production possibility frontier, then:

$$Q_i = \sum_{k=1}^{M} \omega_k \Delta_{ik}^{+} \,, \tag{3}$$

where ω_k denotes the area of region *k* as a share of total area, $\omega_k = \frac{\text{Area of region } k}{\text{Total area of all regions}}$.

Finally, if a breeder releases *N* varieties then the total value of that breeder’s output is given by:

$$Q = \sum_{i=1}^{N} \sum_{k=1}^{M} \omega_k \Delta_{ik}^{+} \tag{4}$$

Equation 4 defines an *ideal* measure of the value of breeders’ output and articulates how this is related to the region-specific performance of the varieties they release. The goal of this article is to assess how plant variety protection in Australia affected breeders’ output, as defined by equation 4. Equation 4 illustrates that an assessment of the effect of the reform on both the performance of varieties released and on the *number* of varieties released is required. The next section detail the empirical approach to measuring the contribution of individual varieties to the production possibility frontier. Measuring the number of varieties released is obviously more straight forward and the impact of plant variety protection on this will also be assessed in the quantitative results.

Data: measuring variety performance

To assess the impact of plant variety protection on breeder output new data was compiled on all 250 milling wheat varieties (hard and soft) released by Australian breeding programs between 1976 and 2011.[7] The data include measures of how each variety performs in 23 regions across Australia, which collectively account for more than 99 percent of Australia's total wheat production. Data pertaining to three attributes of each variety's performance (specific to cultivation in each region) were collected. The three attributes are: yield, end-use quality and disease resistance. Measures of these three attributes are used to generate an index of variety profitability, specific to each region. The data and measures are summarized below and further details regarding the data sources are included at appendix A.

Yield: The data cover the predicted (genetic) yield for each variety in each of the 23 regions in which the variety is relevant. The yield data are derived from randomized replicated scientific variety trials and therefore isolate the genetic contribution. In each agronomic region varieties are tested at between three and nine trial sites. Predicted yield is derived from the average relative performance of each variety at each site across all years available.

End-use quality: Like yield, the end-use quality is determined by the interaction of genetics and the environment in which the variety is grown. Under Australia's nationally standardized approach to grading end-use quality, every single wheat variety is classified according to the market category the harvested grain can be sold into, depending on the region in which it is grown. These market categories are called grades. The market price for each grade (of harvested wheat) provides a measure of the value to consumers of flour milled from each variety. Eight different grades of wheat are distinguished in this analysis. Grade classifications are specific to each variety-region pair i.e., a variety can be given a high grade classification if grown in one region, but be subject to a lower value classification if grown in another region. The market price for each of the eight grades of wheat (average between 1997 and 2008) is reported in table 1.

[Table 1 about here]

Disease resistance: The third attribute incorporated into the measure of variety performance is stripe rust resistance. Stripe rust is a fungal pathogen that is responsible for the greatest disease costs across the Australian wheat industry (Murray and Brennan 2009). Each variety exhibits a different susceptibility to stripe rust. Choosing varieties which incorporate rust resistance is the most cost-effective way farmers can manage stripe rust (Haskins and McMullen 2006; Murray and Brennan 2009). The cost of managing stripe rust is an important intermediate input to wheat farming that varies systematically by variety. Breeding in stripe rust resistance has been a central goal of breeding programs since the disease was first introduced into Australia in 1978 (Simmonds 1989).

Rust resistance is measured using a Likert scale from one (corresponding to immune) to five (corresponding to 'very susceptible'). The data are derived from official published resistance ratings. An estimate of the monetary value of different levels of rust resistance was estimated based on the cost of five representative fungicide programs, corresponding to five points on the resistance scale. The control programs allow for both seed dressings and foliar application and include the cost of the fungicide as well as the cost of application by aerial spraying. The resistance ratings and representative control programs are depicted in table 2. The data on resistance ratings include fractional steps and these were accommodated by using a quadratic prediction of the rust control costs against resistance ratings.[8]

[Table 2 about here]

Variety's contribution to regional production possibility frontier

Using the data described above a new multi-attribute profit index for each wheat variety in each of the 23 regions was calculated. The index can be summarised as:

$$\pi_{ik} = \mathbf{yield}_{ik} \times \mathbf{price}_{ik} - \mathbf{disease\ control\ costs}_{i} \quad (5)$$

Equation 5 states that the expected value of growing variety i in region k is measured by the *yield* multiplied by the *price* per tonne (which is determined by end-use quality) less *disease control costs* (which depend on genetic resistance). As noted previously, all costs of cultivation that are invariant to the choice of variety can be omitted from the profit index, as these will be differenced out. The potential additional profit that can be generated by cultivating variety i (as opposed to the incumbent) is given by: [9]

$$\Delta_{ik} = \pi_{ik} - \pi_{\text{incumbent},k} \quad (6)$$

As noted previously, varieties only contribute to the potential productivity frontier if the potential additional profit is positive (as in equation 2). However, truncating the estimated potential additional profit at zero involves discarding a great deal of information. More importantly, truncation at zero fails to account for the fact that potential additional profit is measured with error. Even where a variety's predicted performance is below the frontier, there is some probability that it will outperform the frontier. One way of thinking about this measurement error is that the agro-ecological regions exhibit intra-regional environmental heterogeneity, so the performance of each variety differs across locations within each region. A variety whose expected performance in a region is marginally below the frontier may in practice prove to be the best at a specific sub-regional location.

Reflecting the above discussion, instead of simply truncating at zero (that is, applying equation 2), the measure is transformed to reflect the variety's potential contribution to the production possibility frontier under the hypothetical that *the variety is grown everywhere it out-performs the incumbent*. To do this, assume that the actual additional profit that is achievable by sowing variety *i* at any randomly selected location within region *k* conforms to a distribution denoted by $\Delta_{ik} \sim F\left(\Delta_{ik}\right)$. Then the share of area of region *k* in which the variety outperforms the frontier is given by $\Pr\left(\Delta_{ik} > 0\right)$ and the contribution of variety *i* to the production possibility frontier is given by: [10]

$$\Delta_{ik}^{*} = \int_{\Delta_{ik}=0}^{\infty} \Delta_{ik} . f\left(\Delta_{ik}\right) d\Delta_{ik} \tag{2'}$$

This can be calculated in practice given the specific distribution of Δ_{ik}. Assuming Δ_{ik} is normally distributed with mean $\mu_{\Delta_{ik}}$ and variance $\sigma_{\Delta_{ik}}^{2}$, then Δ_{ik}^{*} is given by (see appendix A for derivation):

$$\Delta_{ik}^{*} = \mu_{ik} \Phi_{0,\sigma_{ik}}\left(\mu_{ik}\right) + \frac{\sigma_{ik}}{\sqrt{2\pi}} . e^{\frac{-\mu_{ik}^{2}}{2\sigma_{ik}^{2}}} \tag{2''}$$

where $\Phi_{0,\sigma}$ represents the Normal cumulative distribution function with mean zero and variance of $\sigma^2_{\Delta_{ik}}$.

The relationship between a variety's expected additional profit $\left(\Delta_{ik}\right)$ and its strictly positive contribution to the production possibility frontier $\left(\Delta^*_{ik}\right)$ (i.e., equation $2"$) is depicted in figure 1. The horizontal axis depicts the (measured) expected additional profit, which can take positive or negative values (it is negative if the performance of the variety is below the existing frontier). The vertical axis depicts the variety's contribution to the potential productivity frontier (i.e., Δ^*_{ik}) – this is the additional value-added per hectare that can be generated if the new variety is sown everywhere it outperforms the incumbent. Note that the transformation resembles truncation at zero – in fact it would be equivalent to truncation at zero if expected additional profit were observed perfectly (i.e., $\sigma^2_{\Delta_{ik}} = 0$).

[Figure 1 about here]

Calculating Δ^*_{ik} requires data for the expected potential additional profit and its variance. The measure of expected additional profit is described above (equations 6). A uniform estimate of the standard deviation of the profitability of 70 (i.e., $\sigma_{\Delta_{ik}} = 70$) is used, which reflects measured variance of predicted yield scaled by price plus an estimated contribution to variance from the value of rust resistance.[11] Values of standard deviation between 40 and 100 were considered as robustness checks. Using a uniform variance estimate preserves the ordinal rank of predicted performance of each variety.

The measured contribution to the frontier also needs to be weighted to account for the fact that trial regions differ in size. To do this, new data were collected on the area of each test region. These data reflect the total area of land actually used for wheat cultivation in practice. To generate the data, maps of the trial regions were geo-coded and linked to Australian agricultural census data (ABS 2013). The area share of each trial region is given by:

$$\omega_k = \frac{\text{Hetares of wheat cultivated in trial region } k}{\text{Total hectares of wheat cultivated in all regions}} \tag{7}$$

The preferred dependent variable used in the regressions is the area-weighted contribution to achievable value-added of variety *i*, which is given by:

$$\Delta_{ik}^{A} = \omega_k \Delta_{ik}^{*} \tag{8}$$

Estimating equation and statistical approach

To assess how plant variety protection has affected the contribution of varieties released to the production possibility frontier of Australian farmland, the canonical estimating equation is given by:

$$\Delta_{ik}^{A} = f\left(\text{PVP}_i, \text{Clearfield}_i,\ \text{Hybrid}_i,\ \text{Year}_i\right) \tag{9}$$

where Δ_{ik}^{A} is defined in equation (8); PVP_i is an indicator of the role of plant variety protection in the development of variety *i*; Clearfield_i is a binary indicator of whether variety *i* expresses tolerance to imidazolinone herbicides; Hybrid_i is a dummy indicator that equals one if the variety is a hybrid; and, Year_i is the year the variety was released. The independent variables are described below.

Measuring plant variety protection

Recall that after the introduction of plant variety protection in 1994, breeders' transitioned to royalty funded business model as government funding was progressively withdrawn. Each breeder adopted plant variety protection at different rates. Public breeders were privatized and new private firms entered the market. Private breeders charge royalties on all varieties released. To measure of the role of plant variety protection in the development of each variety I use an indicator of the extent to which each breeder appears to conform to a royalty funded business model at the time the variety was bred.

The indicator employed is a three-year moving average of the share of varieties released on which end-point royalties apply. Using a three year moving average, centred five years before the release year of variety *i*, accommodates the fact that breeders do not release varieties every year and the impact of any change to breeder performance will not manifest in the stable of varieties released for at least five years. To reiterate: the variable PVP does not reflect the registration status of variety *i*, rather it reflects the propensity of the breeder of variety *i* to charge end-point royalties on their varieties.

Control variables

Since variety performance data come from randomised replicated scientific variety trials, the model does not need to include environmental variables such as rainfall or soil type in order to derive unbiased estimates of the impact of plant variety protection on breeder output. Other control variables which are included are described below.

Hybrid. A few hybrid varieties of wheat were released in Australia prior to the introduction of plant breeders' rights. These were some of the first (and only) hybrid wheat varieties commercialised globally. Hybridisation provides *de facto* protection against expropriation. Hybrid varieties also exhibit systematically higher yield than self-pollinating varieties but are more costly to produce (Cisar and Cooper 2006). The model includes a dummy variable which designates whether a variety is a hybrid and the sign on the estimated coefficient is expected to be positive.

Clearfield. Wheat varieties which carry genes conferring tolerance to imidazolinone herbicides are marketed as Clearfield™. The advantage to farmers of growing Clearfield wheats is that imidazolinone herbicide can be used to control weeds without damaging the wheat crop. However, the benefits of Clearfield must be weighed against the lower yield exhibited by varieties expressing the Clearfield trait. The model includes a dummy variable which designates whether a variety carries the Clearfield trait since there is no systematic way to incorporate the value of the Clearfield trait in the profit index directly. The estimated coefficient is anticipated to be negative.

Year of release. To control for any underlying counterfactual trend in breeding output over time the model includes the variety year of release. The expected coefficient is ambiguous. If, as with the proverbial 'low hanging fruit,' all of the easiest, biggest improvements are made early, this would suggest a concave underlying trend, and a negative coefficient on the trend variable. In contrast, if breeders are 'standing on the shoulders of giants' and advances in molecular biology and genomics are making the achievement of big advances in performance more rapid, the underlying trend will be convex and the coefficient will be positive.

Summary statistics of all variables used in the regression are presented in table 3. The first panel shows measures of the performance of each variety in each region for which data are available. The average expected yield is 2.73 tonnes per hectare and average profit index is $662 AUD per hectare. The average newly released variety exhibits a predicted yield that is below the incumbent by 0.30 tonnes, and would achieve $101 less profit per hectare than the incumbent (on average, across all regions in which it is tested). The average increase in achievable value-added if the variety is sown strictly where it outperforms the frontier is $4, and when weighted by area of regions this increase is $4.5 per hectare.

[Table 3 about here]

Statistical estimator

The functional relationship is assumed to be log-linear since the dependent variable (variety contribution to regional production possibility frontier) is non-negative. The estimating equation is given by:

$$\Delta_{ik}^{A} = e^{\beta x_i} \varepsilon_{ik} \tag{10}$$

where covariates are represented by vector $x_i = \left(PVP_i, Clearfield_i, Hybrid_i, Year_i\right)'$ and ε_{ik} reflects random error, such that $E\left(\varepsilon_{ik} \mid x\right) = 1$. The disadvantages of log linearizing and using OLS in the case of skewed non-negative variables are well documented (Manning and Mullahy 2001; Santos Silva and Tenreyro 2006; 2011; Martínez-Zarzoso 2013). *Inter alia,* log linear OLS estimates are inconsistent in the presence of heteroskedasticity and the log transformation is undefined for observations that are zero.[12] Equation (10) is estimated using a gamma quasi-maximum likelihood estimator (QML). This approach avoids the need to log transform the dependent variable and consistency relies only on the moment conditions. The approach allows for heteroskedasticity through the choice of distributional family. A Modified Park Test (Manning and Mullahy 2001) indicates that the data fits a Gamma distribution well.[13] The QML approach is used widely to model analogous (non-zero, skewed) measures such as health care costs, wages and international trade flows (Manning and Mullahy 2001; Blackburn 2007; Santos Silva and Tenreyro 2006; 2011; Martínez-Zarzoso 2013). Estimates using log-linear OLS model are similar and are discussed as part of the robustness tests.

Results and discussion

As a preliminary exercise, a model of potential additional profitability (Δ_{ik}, as defined by equation 6) is estimated. This provides a useful baseline since expected additional profit is measured directly (i.e., no transformation according to equation 2"). As noted, potential additional profitability can be positive or negative, depending on whether the variety outperforms the incumbent and, as a consequence, the size or the estimated coefficients are not straightforward to interpret. Yet, the analytical framework developed in this article illustrates measured additional profit is correlated with the variety's contribution to the frontier.

The data are first analysed for a structural shift potentially coincident with the introduction of plant variety protection. Rather than assume the structural break occurred in a specific year, a flexible approach is adopted by including a set of four 3-year period dummies (the omitted class are varieties released prior to 1994). The model is estimated using OLS with errors robust to unknown heteroskedasticity. Results are presented in column (1) of table (4). These indicate that the potential additional profit achievable by varieties released after 1999 is $45 per hectare *less* than those released in previous years. This decline coincides with the sixth anniversary after the introduction of plant variety protection which is suggestive that the reform led to a reduction in breeder output (recalling that any possible effect of policy is anticipated to first appear no fewer than five years later).

[Table 4 about here]

Column (2) of table (4) presents another model of potential additional profit, this time including the indicator of how extensively each breeder had adopted the use of plant variety protection. The result suggests that a variety released by a breeder who charges royalties on all varieties they release will generate $18 less additional profit than a variety released by a breeder not using plant variety protection. While the sign on this coefficient is informative, there is no intuitive interpretation of the magnitude of this coefficient since the average new variety does not outperform the frontier (in the average region). Additionally, the results also do not reflect differences area of adaptation of each variety.

Column (3) presents the QML estimates for the model of the area-weighted contribution to the frontier in each region (i.e., Δ_{ik}^{A}, defined in equation 10). In this model, the coefficient on breeders' use of plant variety protection reflects the marginal effect of being more 'royalty funded' on variety performance (in proportional terms). The results show that a variety released by a breeder who charges royalties on all varieties they release contributes 24 percent less to the frontier than a variety released by a breeder who does not charge royalties.

The results suggest that plant variety protection led to a decline in the average 'inventive step' of new varieties released. This finding is consistent with a number of parallel trends observed in Australia's wheat farming sector. First, the rate at which farmers are adopting new varieties has slowed markedly in recent years (White 2011). The fact that farmers are increasingly choosing to cultivate older varieties rather than quickly adopting newly released varieties is consistent with a finding that new varieties are not offering a sufficient performance improvement. Second, the result is consistent with the observed decline in productivity growth of broad acre agriculture in Australia over the period (see Sheng, Mullen and Zhao 2010).

The other estimated coefficients conform to our priors. Hybrid wheat varieties exhibit a substantial value premium, owing to their higher yield. Varieties expressing the Clearfield trait make a lower contribution to observed achievable profit, though of course this does not take into account the lower costs to farmers due to herbicide resistance. Finally, the negative coefficient on year-of-release suggests that rate of expansion of the frontier is decreasing over time, independently of the introduction of plant variety protection.

Further robustness checks of the main result were undertaken. One possible concern arises because varieties are not tested in all regions. This is common with variety trials and is not specific to the Australian system. Expected performance plays some role in determining the regions in which varieties are tested, because varieties are always tested in regions that they are intended to be grown. On the other hand, *ceteris paribus*, the more regions a variety is tested in the lower will be its average observed performance advantage.[14] In practice, it appears that out-performing the incumbent is not a good predictor of selection into a trial region since in the majority of observations the tested variety performs considerably worse than the incumbent.

In any case, the possibility that sample selection may be biasing the result was examined by way of a Heckman Selection Model (Heckman 1979). The approach involves estimating a selection equation (a model of selection into each trial region) and also an outcome equation. Since the Heckman model is linear, the outcome equation models the potential additional profitability so to objective here is to robustness test the sign of the key result. To identify the selection equation I exploit a reform to the administration of scientific crop variety trials, characterised by a shift from state based administration to national (Australia-wide) administration. Varieties included in the national trial system are generally trialled in more regions. The exclusion restriction is a dummy variable indicating that the variety is included in the national trial scheme. There is no statistical test of the validity of the exclusion restriction. However, there is a sound *a priori* case that the institutional reform is exogenous and further, the excluded variable is not found to be significant in a reduced form model of the outcome variable. Results are presented in table (5). Results of the selection model are presented in column (2) and (3) of table (5). The parameter *rho* reflects the correlation between the errors in the selection and outcome equation and this is not significant. The result is qualitatively the same as the GLM estimates, and almost identical to the OLS model presented in column (2) of table (4).

[Table 5 about here]

A number or additional robustness tests were undertaken. The model was re-estimated using a dummy variable indicating whether the breeder is nominally a private firm as an alternative indicator of the role of plant variety protection in variety development (in place of the indicator of the extent of each breeder's use of royalties). This is potentially informative since privatisation was comprehensive and directly attributable to the introduction of plant variety protection. The results are also robust to including breeder fixed effects (for those breeders which existed before the policy reform).

So far, the results above show that plant variety protection is associated with a decline in the average contribution to the frontier of each variety released. However, by releasing more varieties each year breeders could, in theory, increase their total output – even if the contribution of each individual variety is lower (see equation 4). It remains a possibility that the introduction of plant variety protection induced a greater *number* of varieties to be released each year.

Estimating the effect of plant variety protection on the number of varieties released is complicated by the fact that the number of varieties released *per breeder* is dependent on the structure of the industry. For example, market entry increases the total number of varieties released but may reduce the average number of varieties released per breeder per year if the entrant releases only few varieties annually. The statistical approach therefore needs to accommodate market entry and merger and acquisition. As such, two models were estimated using different units of analysis. The first model considers the determinants of the number of varieties released per year per breeder (denoted by N_{tj}). To accommodate merger and acquisitions in this case, varieties released under the moniker of the new private consolidated group are attributed to the original (pre-merger) breeding program. The second model considers the total number of varieties released per year by all breeders combined (denoted by $N_{t,Total}$). In both cases the dependent variable is an integer but show no excess zeros so a negative binomial estimator is used. Models are estimated which examine possible structural breaks coincident with the expected impact of the policy and also including the breeder specific measure of the use of plant variety protection.

Columns (1) and (2) of table (5) present negative binomial count models of the number of varieties released per annum by each breeder. Columns (3) and (4) show analogous model of the total number of varieties released each year by all breeders combined. The coefficient on year of release is positive and significant, indicating that the number of varieties released each year increased over the study period. However, there is no evidence that plant variety protection is associated with an increase in the number of varieties released per year – either per breeder or in aggregate.

[Table 6 about here]

The statistical analysis indicates that the introduction of plant variety protection, and associated reforms, led to a reduction in the output of Australian wheat breeders. There are two principal remaining caveats to this finding. The first is that variety improvement may have increased along a dimension not captured in the profit index developed for this analysis. For example, varieties which are identical according to the observables may possibly be distinguished by varying resistance to another pathogen, propensity for early sprouting, or transpiration efficiency. However, it might reasonably be argued that meaningful improvement over the long term will require improvements in yield, end-use quality and rust resistance. Finally, while the results indicate that the decline in breeder output has been persistent, it remains an open question as to whether institutional teething problems may be resolved leading to higher levels of breeder output in the future. That said, it has now been almost 20 years since plant variety protection was introduced in Australia.

Conclusion

New seed varieties make a substantial contribution to crop productivity growth and will be crucial to feeding a growing population in a hotter drier future. Government breeders remain the main source of new varieties of self-pollinating crops, such as wheat and rice, both in the developing world and in much of the developed world, including the U.S. and Canada. Consistently high estimates of the rate of return on investment in crop breeding suggest chronic underinvestment (Brennan, Martin and Mullen 2005; Galushko and Gray 2008; Alston, Anderson James *et al.* 2011; Heisey, Lantican, and Dubin 2002). In light of this, a great deal of hope is pinned on the power of plant variety protection to drive increased private investment in crop breeding to improve farm productivity and underpin global food security.

Australia's wheat breeding sector represents a veritable ‘pilot study’ through which to understand better how breeder output responds to the introduction of strong plant variety protection. The Australian experience demonstrates that plant variety protection can support a private wheat breeding sector. However, the results presented in this article show that the shift to royalty funded breeding led to a reduction breeder output. The average new variety released by a breeder operating in a royalty funded paradigm is found to contribute 24 precent less to the production possibility frontier than the average variety released by a breeder under the pre-reform regime. The number of varieties released per year does not appear to have been affected by the shift to royalty funded breeding.

The observed decline in breeder output will certainly be an unwelcome development for Australian wheat farmers. The decline in breeder output also indicates that the reforms almost certainly reduced social welfare. The possibility that any reduced investment was greater than the value of foregone farm productivity is remote in light of the high social rate of return to breeding investment that has been reported by numerous studies. Evidence also appears to rule out the possibility that the reforms sped up the rate of adoption of new varieties, which might otherwise offset the welfare reducing effect of decreased breeder output (White 2011).

While plant variety protection is beneficial in encouraging private breeding activity, the evidence presented in this article leads to the conclusion that, in isolation, it does not generate the *welfare maximising* rate of variety improvement. The policy implication of this finding is that complementary intervention is warranted. The appropriate policy response could involve either subsidising private breeding programs or maintaining public breeding programs, possibly complementary to a private sector. In order to identify the most effective policy instrument further analysis is required to understand the extent to which the decline in breeder output reflects reduced productivity or reduced investment.

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Tables and figures

Table 1 Wheat Grades descriptions and prices ($A average prices 1997-2008)

Grade classification		Price per tonne
Prime hard	Minimum protein content of 13% hard-grained varieties Prime hard varieties Excellent milling quality high dough strength and functionality	$274
Hard	Minimum protein content of 11.5% hard-grained varieties Superior milling quality Good dough strength and functionality	$259
Noodle	Protein content 9.6-11.5% Soft grained varieties Very good noodle quality	$261
Soft	Soft grained varieties Maximum protein content of 9.5% Weak dough with low water absorption	$257
Premium White	Minimum protein content of 10% hard-grained varieties high milling performance	$242
Standard White	Protein content less than 10% unless Australian Standard White classification	$232
General Purpose†	Default classification and wheat that fails to meet higher milling grain receive standards.	$225
Feed†	Wheat suitable for animal feed	$199

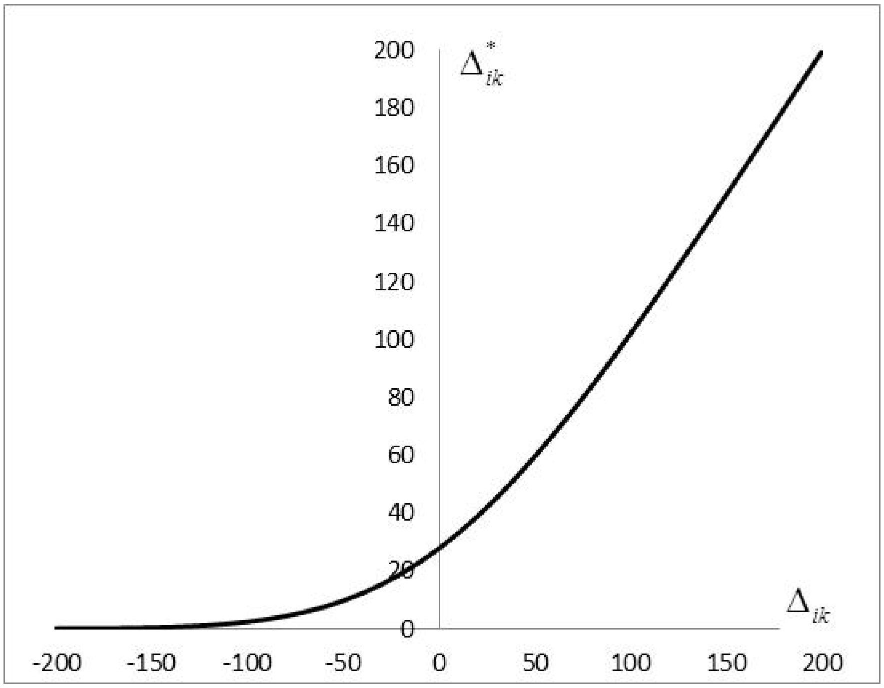
Source: DAFWA (2009) Blakeney, Cracknell and Crosbie *et al.* (2009). Notes: †'General Purpose' is a default classification given to wheat grown outside their recommended region or grain with another idiosyncratic quality fault. The sample does not include varieties bred specifically for feed of chaff, however, a few milling varieties are classified as feed grade in some regions.

Table 2 Rust ratings and representative control costs

	Seed Dressing			Foliar application				Total Cost
Rating	**Fungicide**	**Rate / 100 kg**	**Subtotal (seed)**	**Fungicide**	**Rate (ml/ha)**	**Applications**	**subtotal foliar cost**	
Very Susceptible	Fluquinazole	450	$11.99	Expoxiconazole	375	2	$52.26	$64.25
Susceptible	Fluquinazole	450	$11.99	Expoxiconazole	375	1	$26.13	$38.12
Moderately Susceptible	Triadimenol	150	$2.54	Propiconazole	375	1	$17.50	$20.04
Moderately Resistant	Triadimenol	150	$2.54	Triadimefon	750	1	$11.85	$14.39
Resistant	Triadimenol	100	$1.69	-	-	-	-	$1.69
Very Resistant		-	-	-	-		-	$0.00

Source: Brennan and Murray (2009), Haskins and McMullen (2006) and Moteley (2007), McRae, McCaffery and Matthews (2010). Thanks are due to John Brennan for advice in developing these.

Figure 1. Contribution to the frontier as a function of measured additional profit



Source: simulation of Δ^*_{ik} transformation for the range of observed Δ_{ik} with $\sigma = 70$

Table 3 Summary statistics for regression sample

Measures of region-specific ‘performance’	Variable	Mean	s.d.	Min	Max
yield per hectare	$yield_{ik}$	2.73	0.69	0.60	5.10
yield advantage:	$y_{ik} = yield_{ik} - yield_{\max k}$	-0.30	0.30	-1.49	1.38
Profit index	π_{ik}	662	181	127	1239
Additional profit	$\Delta_{ik} = \pi_{ik} - \pi_{\max k}$	-101	84	-434	244
Contribution to frontier‡	Δ^{*}_{ik}	4.03	6.75	0.00	111
Area-weighted contribution to the frontier‡	$\Delta^{A}_{ik} = \omega_k \Delta^{*}_{ik}$	4.53	8.90	0.00	90.8
Explanatory variables					
Breeders use of PVP	PVP_i	0.40	0.47	0	1
Hybrid variety	Hybrid_i	0.02	0.14	0	1
Clearfield	Clearfield_i	0.04	0.20	0	1
Year of release	T	1998	10	1976	2011

Notes: Total number of variety-region observations is 2265. ‡ For illustrative purposes, in this table, contribution to the frontier and area weighted contribution to the frontier are expressed in units of dollars of additional profit generated per composite hectare per variety. Recall from equation 4 the total contribution of N varieties to the aggregate frontier defined by M regions is given by: $\sum_{i=1}^{N}\sum_{k=1}^{M}\omega_k \Delta^{*}_{ik}$. The average contribution per variety can be retrieved from the sample average as $\left(\frac{\sum_{i=1}^{N}\sum_{k=1}^{M}\omega_k \Delta^{*}_{ik}}{\text{number of observations}}\right) \times \left(\frac{\text{number of observations}}{N}\right)$. In interpreting this as the average variety’s contribution to the frontier, missing observations are implicitly treated as contributing zero.

Table 4 The determinants of variety performance

Dependent variable:	(1) Additional profit Δ_{ik}	(2) Additional profit Δ_{ik}	(3) Area weighted Cont'n to frontier Δ_{ik}^{A}
Estimator:	**OLS**[a]	**OLS**[a]	**QML**[b]
Released between 1994-1996	1.170		
	(6.928)		
Released between 1997-1999	-12.44		
	(7.775)		
Released between 2000-02	-45.94***		
	(8.920)		
Released after 2003	-44.46***		
	1.170		
Breeders use of PVP		-18.07***	-0.244**
		(5.654)	(0.121)
Hybrid	47.19***	54.33***	0.771***
	(9.414)	(9.466)	(0.259)
Clearfield	-32.59***	-35.74***	-0.954***
	(9.002)	(8.400)	(0.181)
Year of release	0.162	-0.646**	-0.0173***
	(0.684)	(0.284)	(0.00575)
Obs.	2,665	2,665	2,665
R-squared	0.065	0.053	

Notes: *** p<0.01, ** p<0.05, * p<0.1. All models include a constant. [a]Robust errors in parenthesis [b]Quasi-Maximum Likelihood Gamma estimate. Modified Park Test of Gamma distribution $\chi^2 = 0.14$, p = 0.70.

Table 5 Determinants of variety performance: additional robustness tests

Dependent Variable	(1) Additional profit Δ_{ik}	(2) Selection $z_{ij} > 0$
Breeders use of PVP	-20.37***	0.433***
	(7.422)	(0.0619)
Hybrid	55.24***	-0.0898
	(11.76)	(0.105)
Clearfield	-37.06***	0.302***
	(8.593)	(0.109)
Year or release	-0.671**	-0.0112***
	(0.267)	(0.00308)
Variety in national trials.		0.515***
		(0.0545)
Observations	5,750	5,750

Notes: *** p<0.01, ** p<0.05, * p<0.1. Estimated using twostep procedure. The correlation in the error terms between the outcome and selection equation (rho) is estimated to be 0.237 and is not statistically significant. All models include a constant.

Table 6. Negative Binomial estimates of the number of varieties released each year

	(1)	(2)	(3)	(4)
Dependent variable:	**Varieties per year per breeder (N_{tj})**		**Varieties per year total ($N_{t,total}$)**	
Released between 1994-1996	-0.263		-0.278	
	(0.354)		(0.499)	
Released between 1997-1999	-0.0891		-0.197	
	(0.353)		(0.394)	
Released between 2000-02	-0.193		-0.185	
	(0.398)		(0.499)	
Released after 2003	-0.378		-0.469	
	(0.481)		(0.631)	
Breeders use of PVP		-0.221		
		(0.252)		
Breeders use of PVP (average over j)				-0.303
				(0.330)
Year of release	0.0386*	0.0312***	0.0359	0.0281**
	(0.0216)	(0.0115)	(0.0274)	(0.0122)
Observations	222	222	34	34

Notes: *** p<0.01, ** p<0.05, * p<0.1. Dispersion parameter is significant indicating the use of a Negative Binomial over a Poisson. All models include a constant.

Appendix A details of data sources

A comprehensive list of wheat varieties released between 1968 and 2009 was first complied using Whiting (2004) the NVT (2011), the IP Australia Plan Breeders Rights database, Ferns *et al.* (1975) and Fitzsimmonds (1998).

Yield

Since 2004, data come from national program of variety trials known as the National Variety Trials (NVT). The National Variety Trials publish predicted yields (Estimated Genetic Values) for each variety included in their trials which is calculated using the methodology outlined in by Smith *et al.* (2001). The NVT includes some varieties released as early as 1982. However, the sample is truncated in that older varieties deemed not relevant are not included in the sample. Missing data were filled from historic state government trial results. Prior to the establishment of the NVT system each individual state government undertook crop variety trials and each year published estimates of variety yield based on multi-year multi-site repeated randomised trials. In order to develop a consistent series State trial data was scaled, using the average difference in estimated yield of all varieties common to both samples. The methodology preserves both the ordinal and proportional yield differences between varieties included in each sample. Historical data come from 57 separate published sowing guides listed below:

Victoria sowing guides (Victorian DPI 1978, 1979, 1983,1985, 1992, 1994, 1996 and 1998). *Yipti* factsheet,(which cites Victorian DPI trials 2000-2004). **Western Australian** sowing guides (DAFWA 1986, 1990, 1999 and 2005). **New South Wales** sowing guides (NSW Agriculture 1980, 1984, 1985, 1987, 1993, 1996, 1999, 2003) and Brennan and Bialowas (2001).

South Australian data, thanks to Rob Wheeler (SARDI 1980 1986 1987 1988 1989 1990 1992-2004). **Queensland** data provided in hard copy by Patt Abbott (QLD DPI 1980 to 2000 except 1997 and 1999).

End use quality

Data on grade classification of each variety are compiled from information published by the Wheat Variety Classification Panel (2010; 2012). For a number of reasons varieties are sometimes reclassified some time after release. The most common shift is downgrading varieties to 'AGP' which discourages farmers to cease cultivating that variety. Historically, to some extent classification has been used as a mechanism to influence on the overall mix of varieties grown. For example, the mix of varieties grown can affect the state-wide susceptibility to disease outbreak which depends on the extent to which susceptible varieties are cultivated. In some instances 'downgrading' reflects that the variety exhibits a genetic defect that was not observed when the variety was first classified. This study uses the grade classified at the time of release and the 2011 grades are considered as a robustness test.

Rust resistance

For the years 2002-2010 data are taken from the University of Sydney Plant Breeding Institute Cereal Rust Reports. Resistance data was collected for each variety in each year to account for the fact that resistance breaks down over time, because new strains of rust fungus continually evolve to overcome the specific resistance gene in varieties.

Historical data were compiled from: Victorian sowing guides in 1983 1985 1992 1993 1994 1996 1997 and 1998; NSW sowing guides for 1982 1983 1984 1985 1986 1987 1988 1989 1990 1992 1993 1994 1995 1997 1998 1999 and 2000; WA sowing guides for 1990 1995 1996

1997 1998 1999 2000 2001 2002 2003 2004 and 2005. Data is available for most varieties in the year of release. The data were cleaned according to the following procedure. Inter year fluctuations which are both preceded and followed by pairs of identical scores are treated as anomalous and replaced with adjacent scores. Other missing data is imputing linearly between trial years or based on a linear prediction using year of release and any available resistance scores for that variety (for any year). If there is no contrasting information available I assume, resistance did not break down for the first 4 years after variety release. Control costs are assumed to be zero before 1979 when stripe rust first affected crops in Australia.

In calculating the costs of the representative rust control programs (summarised in table 2) the national average sowing rate is used (47kg per hectare, see Murray and Brennan 2009).

Variety Origins (Breeder)

Breeder information was come from administrative information from the IP Australia plant variety rights database, Whiting 2004 and data provided by John Brennan (pers comm.).

Year of release

In some instances there was discrepancy between these sources regarding the year of release. The data used are, in order of availability, Whiting (2004), Fitzsimmonds (1998), NVT (2012), Brennan and Bialowas (2002), IP Australia (2012). The PBR registration date is always used if it is the most recent year suggested by the different sources, since it is a requirement of a valid plant breeders right that the variety not be commercially used prior to the application.

Table A.1 Wheat breeding organisations in Australia.

Breeder	Current status
InterGrain	Established 2007. Shareholders are WA Government and the Grains Research and Development Corporation. In August 2010, Monsanto (U.S.) purchased a 19.9% equity share.
Department of Agriculture and Food Western Australia (DAFWA)	Incorporated into InterGrain in 2007
GBA -Grain Biotech Australia	GBA was a private company established in 1998, released 5 varieties between 2003 and 2004. The GBA breeding program largely integrated by InterGrain in 2007
Australian Grain Technologies (AGT)	Established in 2002. Main shareholders include the GRDC, SARDI, the University of Adelaide and Limagrain (France)
South Australian Research and Development Institute (SARDI)	Incorporated into AGT in 2002
University of Adelaide	Incorporated into AGT in 2002
Victorian DPI	Incorporated into AGT in 2002
Queensland DPI	Incorporated into AGT in 2007
New South Wales DPI	Incorporated into AGT in 2007
University of Sydney / Sunprime	The University of Sydney established "Sunprime" to commercialise varieties in 1995. The breeding enterprise was made commercial in 2003 and subsequently in 2005, Sunprime was acquired by AGT.
Hybrid Wheats Australia (HWA)	Produced the worlds first commercially released hybrid wheat. Established mid 1960s. Bought by Cargill in 1983. In 1999 it became part of Sunprime seeds, which in turn was acquired by AGT in 2005.
Longreach.	Established in 2002 by AWB and Syngenta. Currently owned by Pacific seeds (a subsidiary of Advanta, India) and Syngenta.
HRZ Wheats.	A collaboration between CSIRO and the New Zealand Crop and Foor Research. Specializes in High rainfall zone wheat varieties.

Notes: Not listed are a number of cooperative breeding programs which are made up of collaborations between those listed. Two noteworthy examples are: Enterprise Grains Australia (EGA) and Value-added Wheat CRC (VAW). EGA was a partnership between GRDC, DAFWA, QLD DPI and NSW DPI, a second round of EGA did not include DAFWA. The VAWCRC was a partnership of GRDC DAFWA and University of Sydney and focused on soft wheat biscuit varieties. VAWCRC included private partners including Bayer and end users Allied Mills and Arnotts.

Appendix B. Derivation of equation (2")

If Δ is normally distributed $N(\mu,\sigma)$, then (omitting the subscript *i* for expositional clarity):

$$\Delta^* = \int_{\Delta=0}^{\infty} \Delta . f(\Delta) d\Delta = \frac{1}{\sigma\sqrt{2\pi}} \int_{\Delta=0}^{\infty} \Delta . e^{\frac{-(\Delta-\mu)^2}{2\sigma^2}} d\Delta$$

Making the change of variable such that $x = \sqrt{\Delta - \mu}$ so $d\Delta = dx$ we have:

$$= \frac{1}{\sigma\sqrt{2\pi}} \int_{y=0}^{\infty} (\mu + x).e^{\frac{-x^2}{2\sigma^2}} dx = \frac{\mu}{\sigma\sqrt{2\pi}} \int_{y=0}^{\infty} e^{\frac{-x^2}{2\sigma^2}} dx + \frac{1}{\sigma\sqrt{2\pi}} \int_{y=0}^{\infty} x.e^{\frac{-x^2}{2\sigma^2}} dx$$

Considering the first term on the right hand side:

$$\frac{\mu}{\sigma\sqrt{2\pi}} \int_{\Delta=0}^{\infty} e^{\frac{-x^2}{2\sigma^2}} dx = \frac{\mu}{\sigma\sqrt{2\pi}} \int_{x=-\mu}^{\infty} e^{\frac{-x^2}{2\sigma^2}} dx = \mu . \Pr(x > -\mu) = \mu . \Pr(x < \mu) = \mu . \Phi(\mu)$$

where $\Phi_{0,\sigma}$ represents the Normal cumulative distribution function with mean zero and standard deviation of σ.

The second term can be calculated via a second substitution of variables with $z = x^2$ so that $xd\Delta = \frac{dz}{2}$ giving:

$$\frac{1}{\sigma\sqrt{2\pi}} \int_{\Delta=0}^{\infty} x.e^{\frac{-x^2}{2\sigma^2}} dx = \frac{1}{2\sigma\sqrt{2\pi}} \int_{\Delta=0}^{\infty} e^{\frac{-z}{2\sigma^2}} dz = \left[\frac{\sigma}{\sqrt{2\pi}} . e^{\frac{-z}{2\sigma^2}} \right]_{\Delta=0}^{\infty} = \frac{\sigma}{\sqrt{2\pi}} . e^{\frac{-\mu^2}{2\sigma^2}}$$

where the final step is obtained by recalling that $z = x^2 = (\Delta - \mu^2)$.

We can now calculate Δ^+ based on estimates of the mean (μ) and variance (σ) of y as:

$$\Delta^* = \int_{\Delta=0}^{\infty} \Delta_i . f(\Delta) d\Delta = \mu\Phi_{0,\sigma}(\mu) + \frac{\sigma}{\sqrt{2\pi}} . e^{\frac{-\mu^2}{2\sigma^2}}$$

$$\sqrt{\quad}$$

Endnotes

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[1] In this paper I use the term self-pollinating to describe varieties where saved seed perform identically to the parent. The terms ‘open-pollinated’, ‘self-pollinating’, and ‘inbred’ are used in the literature. Technically, wheat is both inbred and self-pollinating and both are important. Self pollinating means the flowers can pollinate themselves Inbred (or homozygous) means the progeny (F1) is bred from parents carrying the same alleles (i.e. genetically the same) for physiological attributes of interest.

[2] Since varieties are generally suitable for a specific agricultural environment Australian breeding programs are the dominant source of varieties for the Australian seed market, and conversely Australia is for the main market for Australian wheat breeders.

[3] Additionally, transgenic (genetically modified) varieties of corn, canola and soybean can be protected from unauthorised cultivation though the patenting system more readily than ‘naturally bred’ cultivars (i.e., cultivars that are not GMOs). To date, there are no transgenic wheat varieties grown commercially.

[4] An earlier version of plant variety protection legislation was passed by Australian parliament in 1987. The 1987 Act did not protect saved seed or crops grown from saved seed and as a consequence had no effect on the wheat breeding industry (Kingwell and Watson 1998; Kingwell 2005).

[5] Technically, welfare is can be improved if investment falls more than the social value of breeder output, though this is neither plausible nor welfare maximising.

[6] The additional value-added achievable per hectare is equivalent to the additional 'profit' achievable per hectare assuming that labour and machinery costs are independent of the choice of variety cultivated.

[7] Durum wheats, as well as purpose bred feed and chaff wheats are not included in the sample.

[8] Stripe rust is present in all wheat growing regions in Australia, though the extent to which environmental conditions are conducive to the disease varies between regions (Murray and Brennan 2009). Differences in rust control costs across the different regions are not modelled since there is no established method or data available for modelling this variation.

[9] The frontier is calculated in the standard manner, as the average of the best three varieties available (at each point in time, in each region).

[10] In practice there are a number of sources of variance including rainfall variation and idiosyncratic within plot trial error (Smith *et al.* 2001). As such, equation 2" should be viewed as the contribution of variety *i* to the potential productivity frontier under the hypothetical that it is sown in all 'instances' where it outperforms the incumbent.

[11] The variance of predicted yields for each variety in each region is published for those varieties included in the National Variety Trial database (55 percent of our sample). For these, the average standard error of predicted yield is 4 percent of the yield (average yield is 2.85 tonnes). Variance associated with the value of rust resistance is estimated to be in the order of $5-10 per hectare. On average stripe rust outbreaks occur in 75 percent of years (Brennan and Murray 2009), implying the variance in any given year is 19 percent, which is scaled by potential cost savings of no more

than $60 p/h (see table 2). No grade 'price premium' risk is included since this is only relevant if the subject variety is of a different grade to the frontier which is rare, and in any case price-premium risk is relatively small and independent of yield risk (Gans 2000).

[12] The dependent variable is skewed as a consequence of observations where variety performance is below the frontier being transformed to values close to zero (see figure 1). Whether measured variety contribution to the regional frontier (transformation given by equation $2'$) is actually zero depends on the distributional assumptions and rounding by the statistical package.

[13] The Modified Park Test models the (squared) estimated residuals as a function of the log of the predictions of the model. A coefficient of 2 indicates a Gamma distribution (that the variance is proportional to the mean). In this case the estimated coefficient was 2.07 with a p-value of 0.71 (under the Null that the coefficient is 2).

[14] Since holding everything else constant, the more regions a variety is tested increases the number of regions that it is not adapted for that it is tested in.